# *Future of Axion Searches*

CPAD Instrumentation Frontier Meeting

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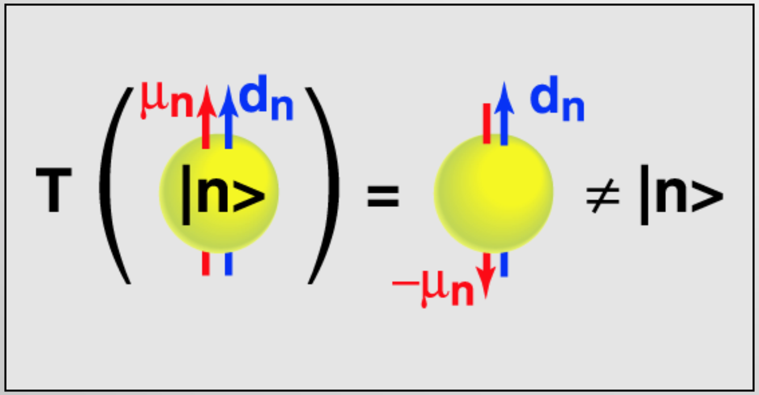
# The axion and the Strong-CP problem

QCD CP violation should, e.g., give a large neutron electric dipole moment ($\cancel{T}$ + CPT = $\cancel{CP}$); none is unobserved.
(9 orders-of-magnitude discrepancy)




**Why doesn't the neutron have an electric dipole moment?**

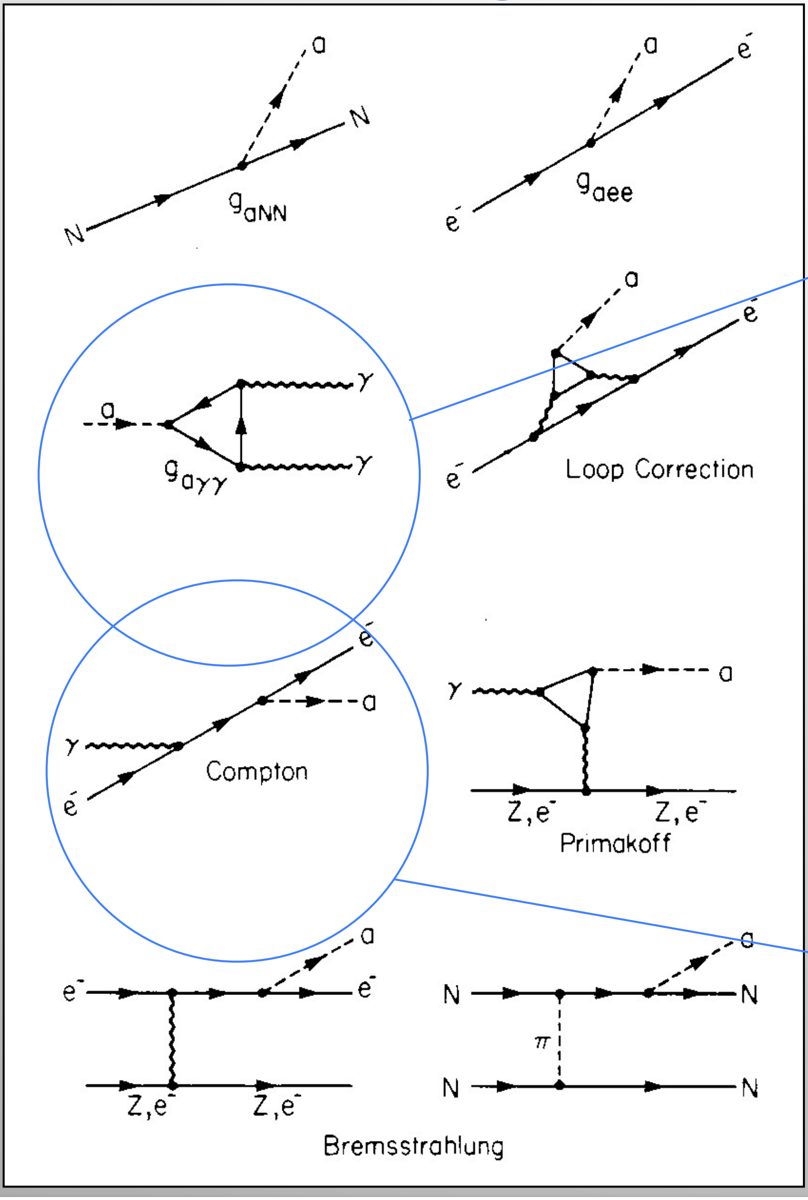
$d_e < 3 \bullet 10^{-26}$ e-cm
Baker et al. 2006

This leads to the "Strong CP Problem": Where did QCD CP violation go?

1977: Peccei and Quinn: Posit a hidden broken U(1) symmetry $\Rightarrow$
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

Axion is a pseudoscalar neutron boson (similar to a very light $\pi^{\circ}$)

# Axion Couplings




Kolb & Turner

<u>Coupling to two photons</u>
Small model uncertainty
Exploited in certain terrestrial searches
Easily calculable

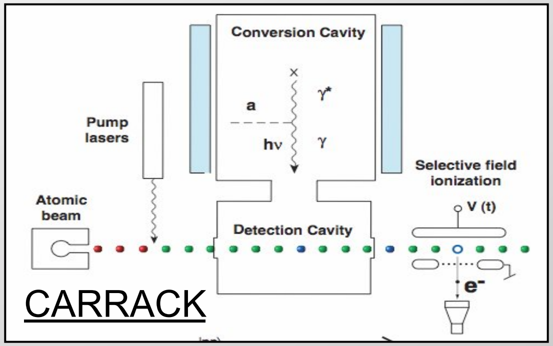
Rate depends on "unification group" (that is, the particles in the loops), ratio of u/d quark masses, and mostly $f_{PQ}$

$$g_{a\gamma\gamma} \sim \frac{\alpha}{f_{PQ}}\left(\frac{E}{N} - 1.95\right)$$

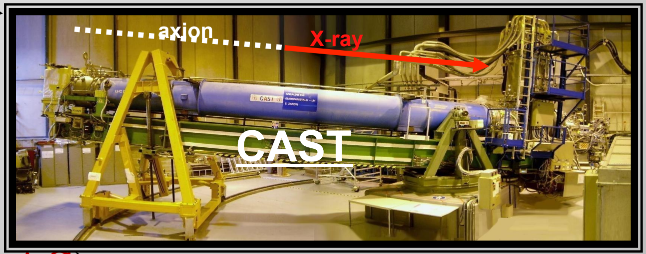
A process with large model uncertainty
Can occur, e.g., in the Sun
Contains unknown $U(1)_{PQ}$ charge of electron

# Variety of experiments*…

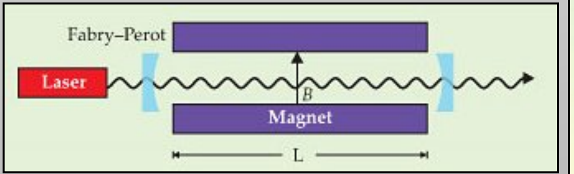
- **Microwave Cavities (dark matter source)**
  - Low noise amplifiers (**ADMX**) and Rubidium Atoms (**CARRACK**)
    - Look for dark matter axions (low mass) converting to photons in B-Field
    - **Relies on a dense source of primordial axions**

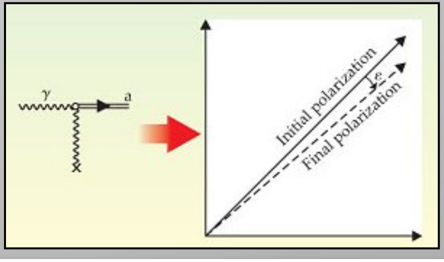



- **Solar Observatories (solar source)**
  - X-Ray (**CAST**) and Germanium detectors
    - Look for axions generated from the sun
    - Higher coupling required than for DM axions.

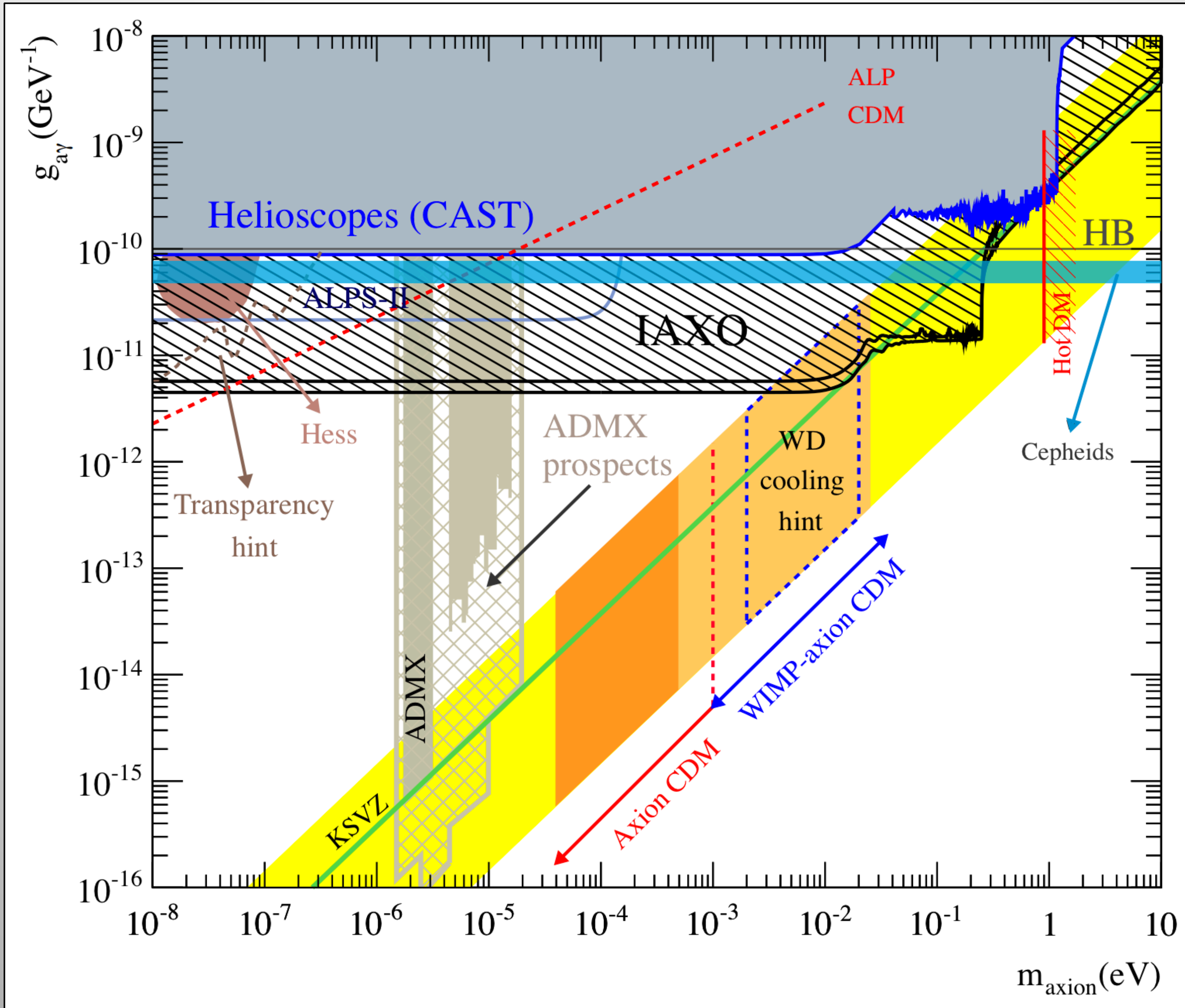



- **Lab experiments (laser source)**
  - Photon regeneration and polarization changes (**PVLAS**)
    - Look for production of axions from light passing through B-field
    - Higher coupling required.
    - Ultralight axions (nano-eV)
    (NMR / LC Circuit)



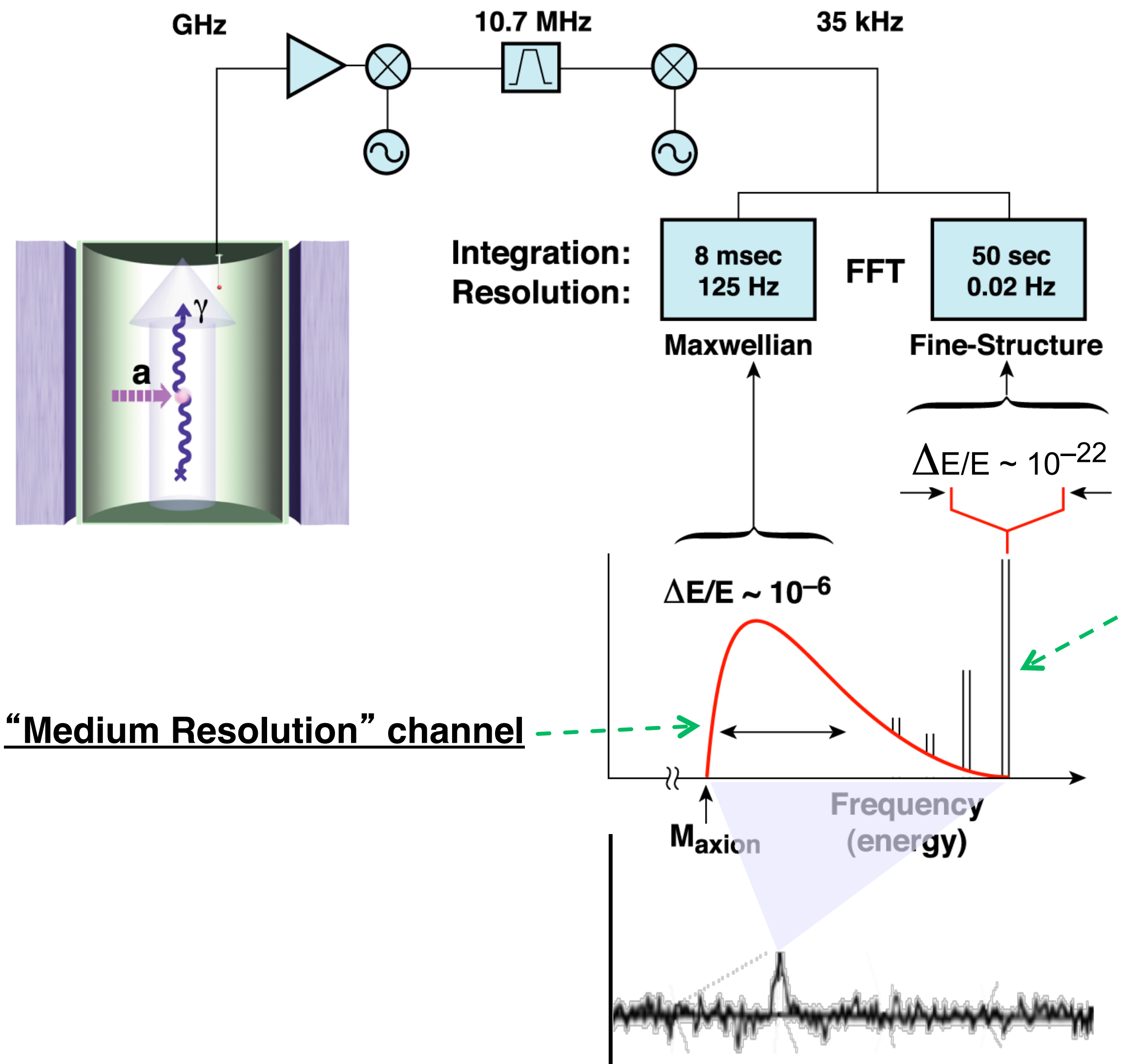




*** See Jeremy Mardon & Surjeet Rajendran talks next**



$g_{a\gamma}$ (GeV$^{-1}$)
Helioscopes (CAST)
ALP CDM
HB
ALPS-II
IAXO
Hot DM
Hess
Transparency hint
ADMX prospects
WD cooling hint
Cepheids
ADMX
KSVZ
Axion CDM
WIMP-axion CDM
$10^{-8}$ $10^{-9}$ $10^{-10}$ $10^{-11}$ $10^{-12}$ $10^{-13}$ $10^{-14}$ $10^{-15}$ $10^{-16}$
$10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ 1 10
$m_{axion}$(eV)

# The Axion Dark Matter eXperiment (original concept from P. Sikivie)




Local Milky Way density:

$\rho_{halo} \sim 450\ MeV/cm^3$

Thus for $m_a \sim 10\ \mu eV$:

$\rho_{halo} \sim 10^{14}\ cm^{-3}$

**"High Resolution" channel**

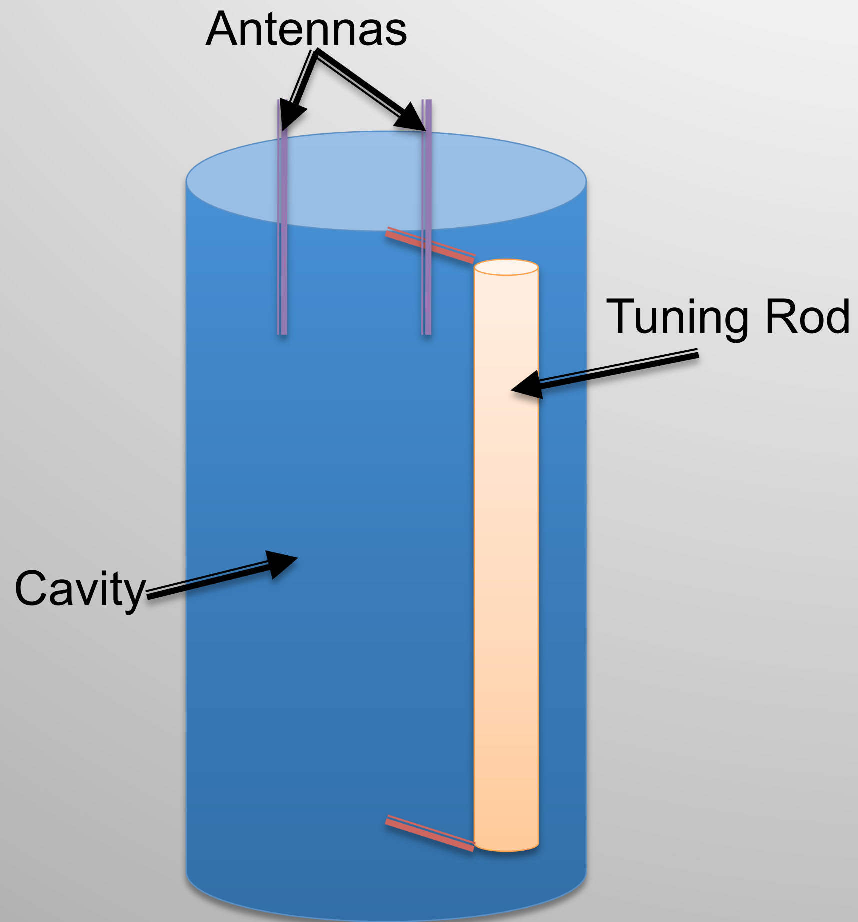
$\beta_{virial} \sim 10^{-3}$ :

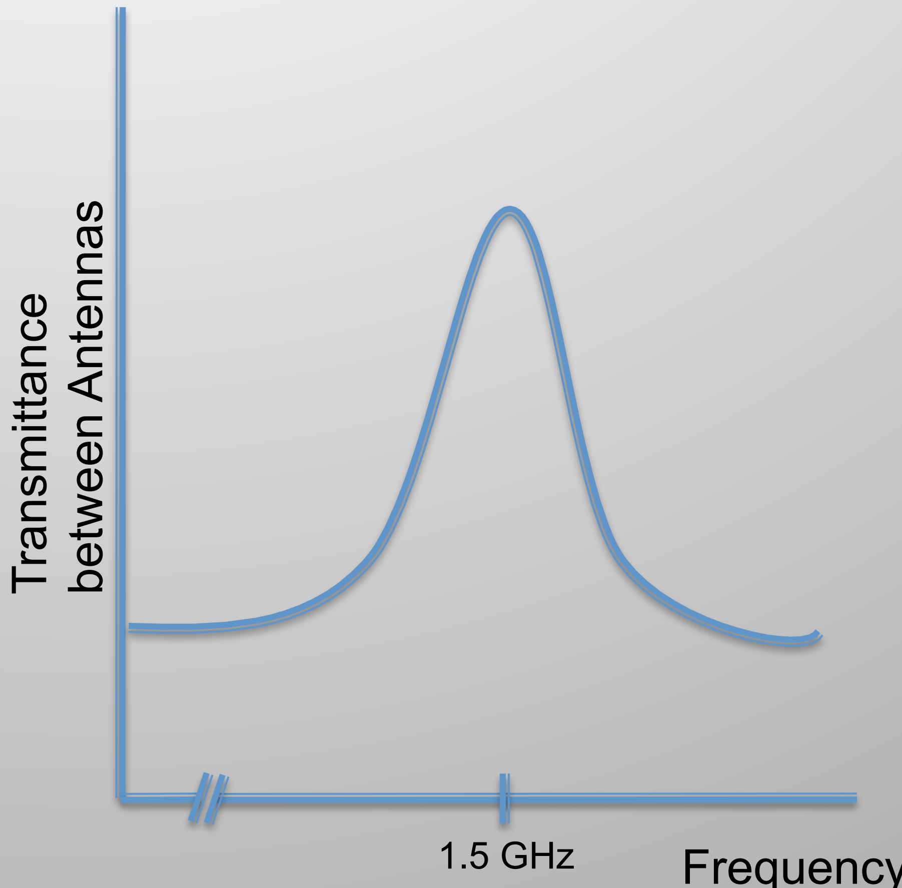
$\lambda_{De\ Broglie} \sim 100\ m$

$\Delta\beta_{flow} \sim 10^{-11}$ :

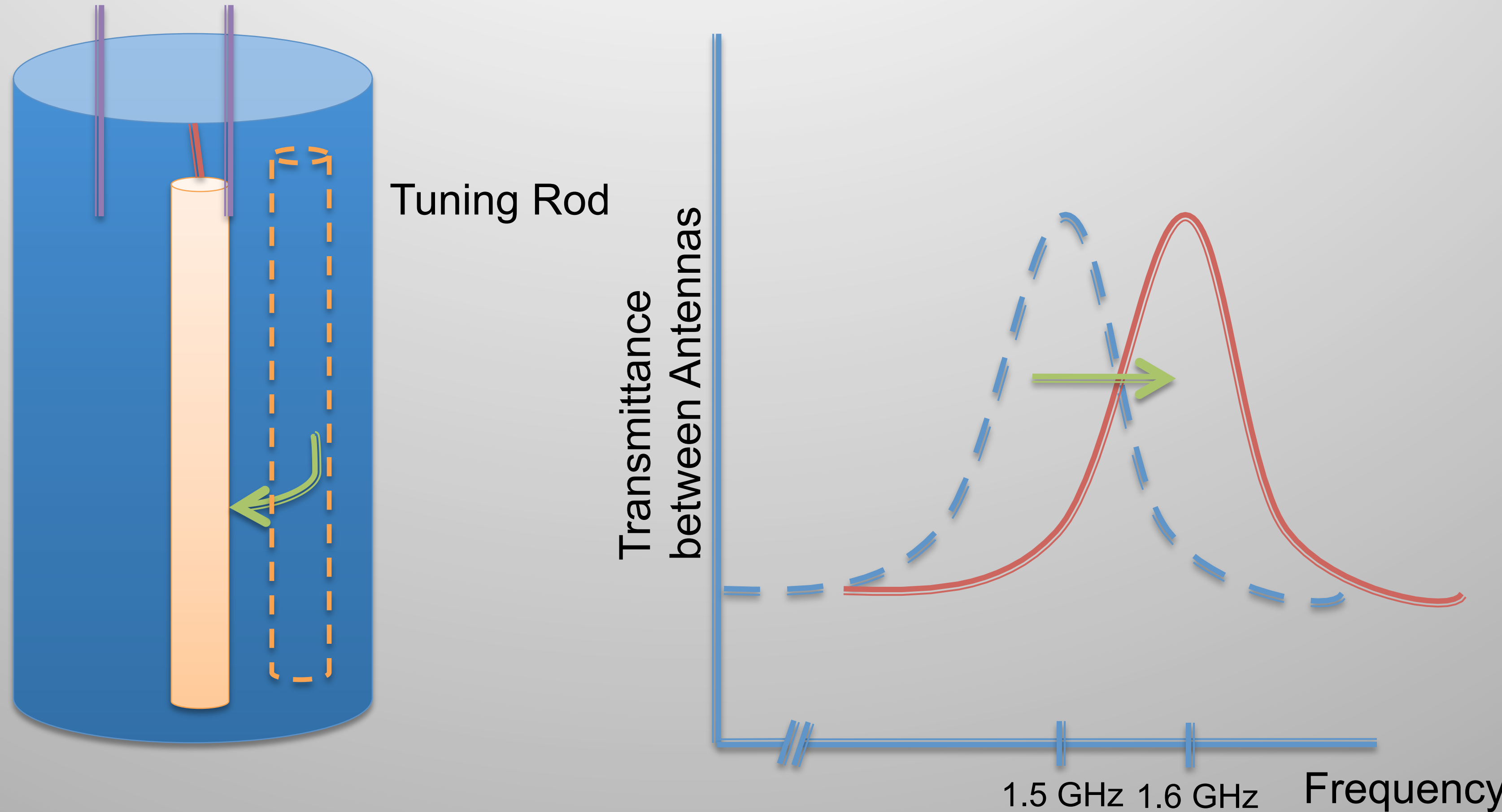
$\lambda_{Coherence} \sim 1000\ km$

# Microwave Cavity needs tunable resonance



# Microwave Cavity needs tunable resonance



# Signal strength

- Power generated in the cavity from axion signal:

$$P_a \approx 3.38^{-23}\, W \left(\frac{V}{100\, l}\right)\left(\frac{B_0}{8\, Tesla}\right)^2 \left(\frac{C_{nml}}{0.5}\right)\left(\frac{g_\gamma}{0.36}\right)^2 \cdot \left(\frac{\rho_a}{0.3\, GeV/cc}\right)\left(\frac{m_a}{1\, GHz}\right)\left(\frac{min(Q_L, Q_a)}{10^5}\right)$$

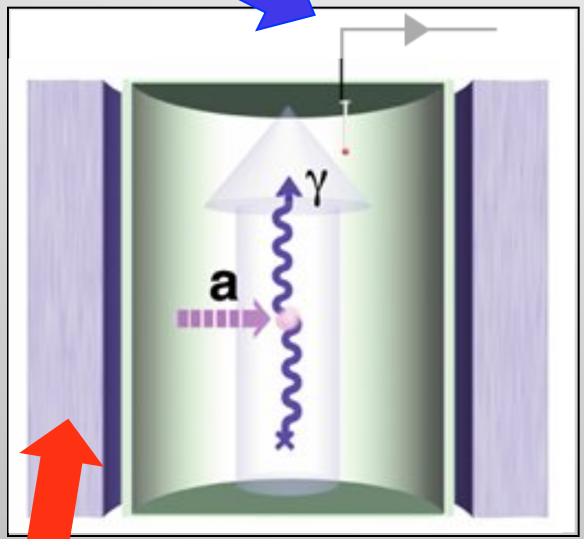
- $\rho_a$ is the local halo density,
- $m_a$ the axion mass (where 1 GHz ~ 4.1 ueV),
- $C_{nml}$ is form factor (overlap of resonant mode E-Field with B-field)
- $Q_L \sim 10^5$ (loaded cavity quality factor); $Q_a \sim 10^6$ (axion line width)
- $g_\gamma \sim 0.97$ (KSVZ); $g_\gamma \sim 0.36$ (DFSZ) are coupling strengths

# The radiometer eqn.* dictates the strategy

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

*But integration time limited to ~ 100 sec*

** Dicke, 1946*




***System noise temp. now***

***$T_S = T + T_N$ ~ 1.5 + 1.5 K***

***But $T_{Quant}$ ~ 30 mK***

**This is where we invested to get to Gen 2**

$$P_{sig} \sim (B^2V\, Q_{cav})(g^2 m_a \rho_a)$$

$\sim 10^{-23}$ *Watts for ADMX*

***But magnet size, strength $B^2V$ ~ \$***

# Scan Rate from Dicke Radiometer equation

- Rate determined from SNR

$$\frac{df}{dt} \approx 750\ MHz/year\ \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{5}{SNR}\right)^2 \left(\frac{f}{1\ GHz}\right)^2 \cdot \left(\frac{B_0}{8\ T}\right)^4 \left(\frac{V}{100l}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

- *SNR* is the Signal-to-Noise for detection (usually set to 5),
- *f* is the frequency being searched (where 1 GHz ~ $m_a$ = 4.1 ueV)
- $T_{sys}$ is the total system temperature ($T_{sys} = T_{cavity} + T_{amps}$)

# The Importance of Low Noise Temperature

- Original system noise temperature: $T_S = T + T_N = 3.2$ K
  - Cavity temperature: $T = 1.5$ K (pumped $^4$He)
  - Amplifier noise temperature: $T_N = 1.7$ K (HEMT)
- Time* to scan the frequency range from $f_1 = 0.5$ to $f_2 = 1$ GHz:

$$\tau(f_1,f_2) = 4 \text{ x } 10^{17}(3.2\text{K}/1\text{ K})^2(1/f_1 - 1/f_2) \text{ sec} \approx \mathbf{130\ years}$$



*Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) theory

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- Next generation (ADMX Gen 2):
  - Cavity temperature: $T = 100$ mK ($^3$He dilution unit)
  - Amplifier noise temperature: $T_N = 50$ mK (MSA)



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- Next generation:

  Cavity temperature: $T = 100$ mK ($^3$He dilution unit)

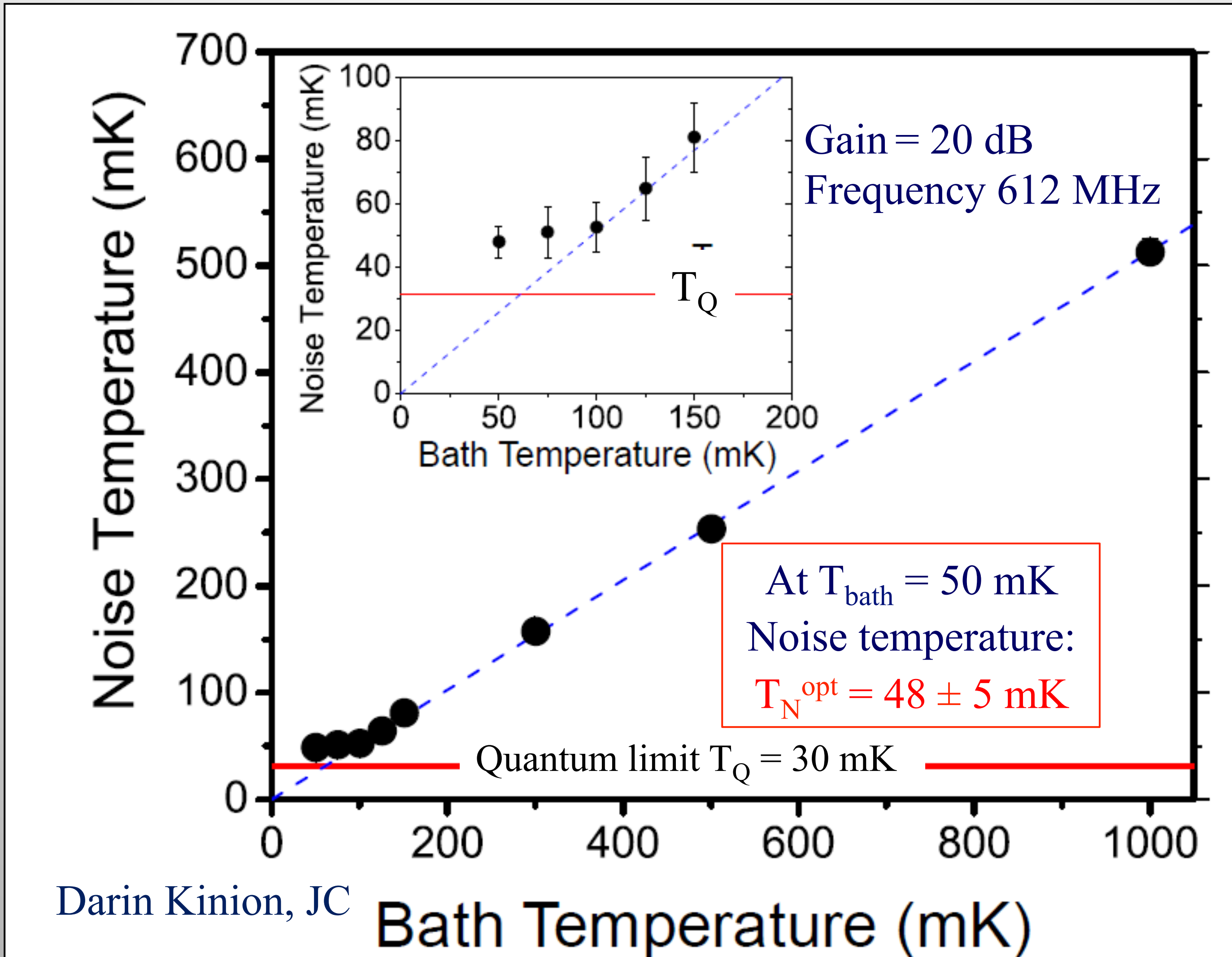
  Amplifier noise temperature: $T_N = 50$ mK (MSA)

- Time* to scan the frequency range from $f_1 = 0.5$ to $f_2 = 1$ GHz:

$$\tau(f_1,f_2) = 4 \times 10^{17}(0.15\text{K}/1\text{ K})^2(1/f_1 - 1/f_2) \text{ sec} \approx \mathbf{104\ days}$$

*Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) theory

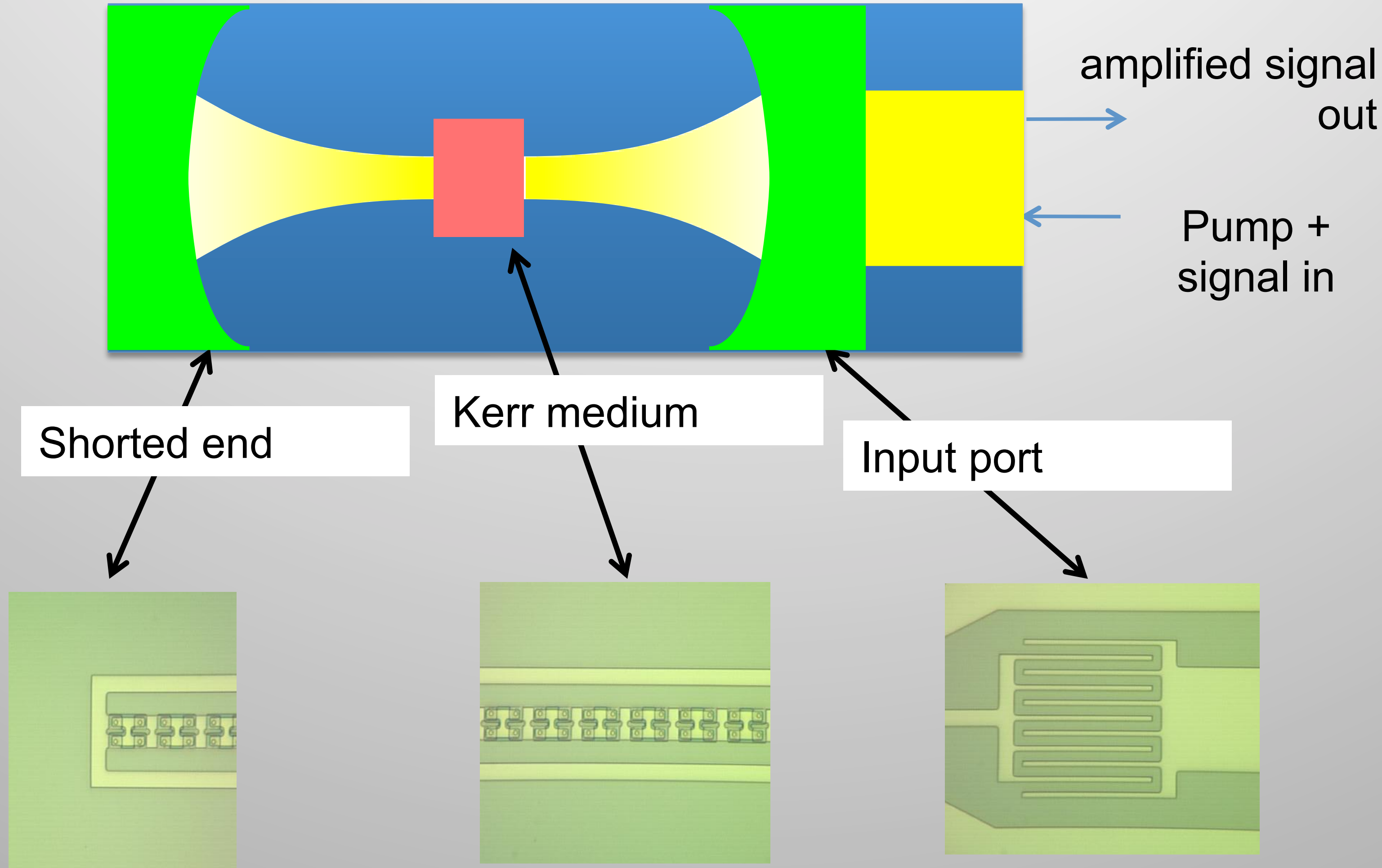
# Enabling Technology: Microstrip SQUID Amps




Noise temperatures of 48 ± 5 mK have been demonstrated at 612 MHz, within 1.7 times the quantum limit

# Josephson Parametric Amplifiers (JPA):

SQUIDs embedded in a cavity form a parametric amplifier




30 $\mu$m

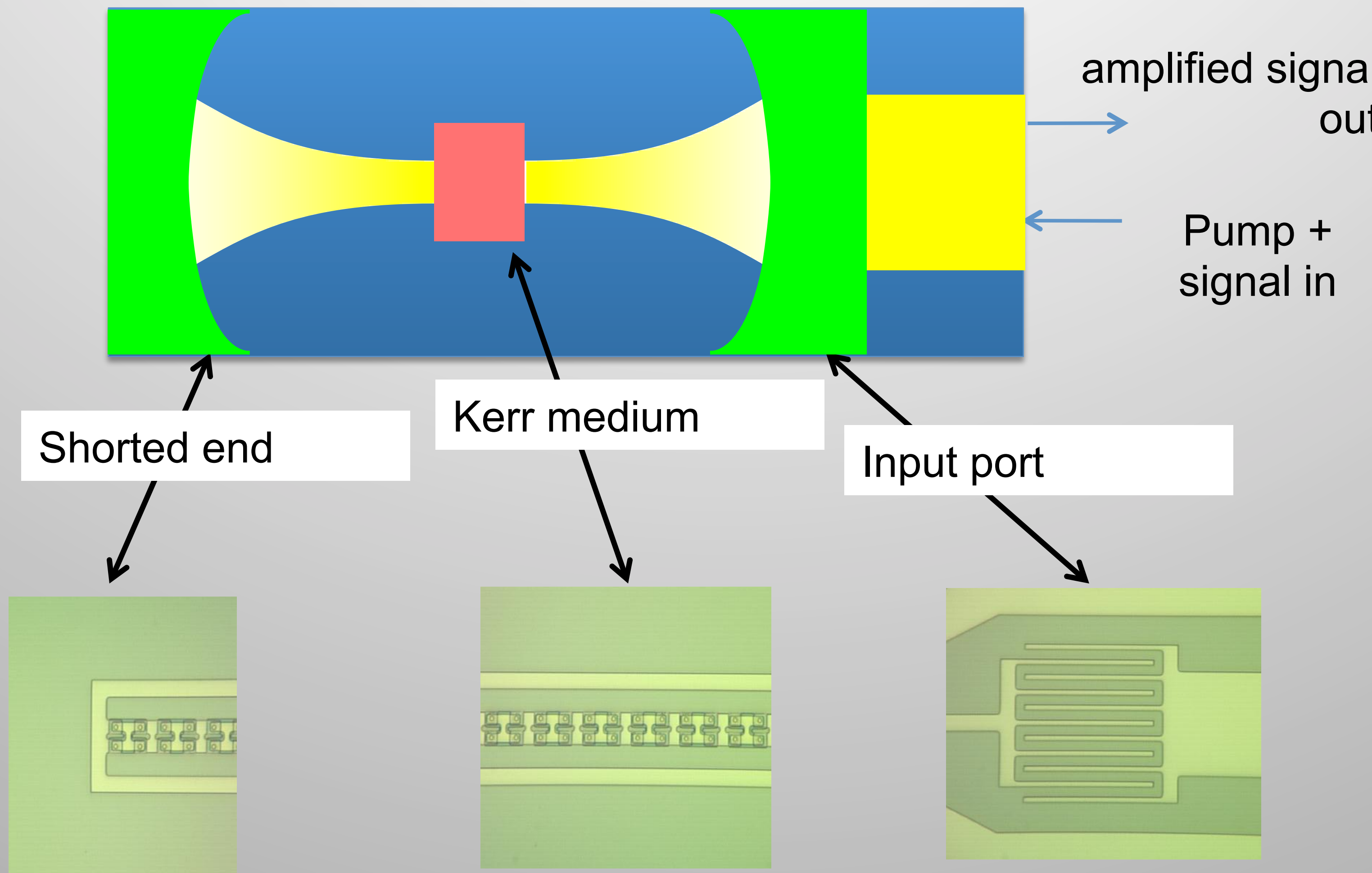
array of 250 SQUIDS
embedded in a CPW resonator

JILA NIST CU

# Josephson Parametric Amplifiers (JPA):

SQUIDs embedded in a cavity form a parametric amplifier

**(see Saptarshi Chaudhuri's quantum amp talk tomorrow)**

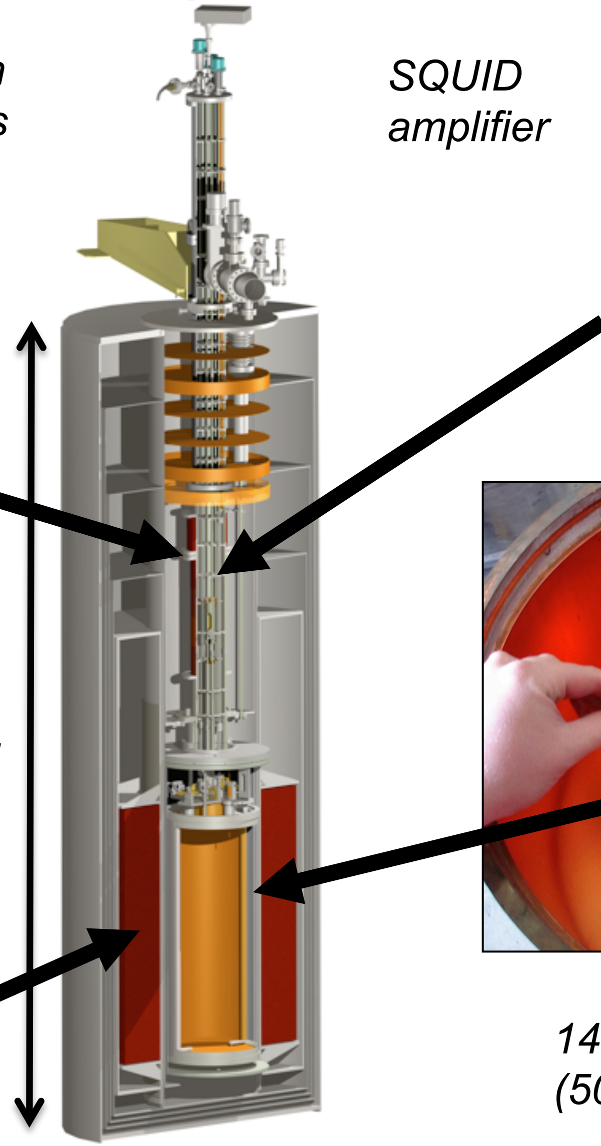



30 μm

array of 250 SQUIDS
embedded in a CPW resonator

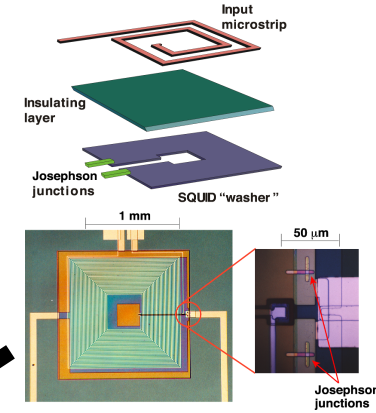
# ADMX Experimental Apparatus

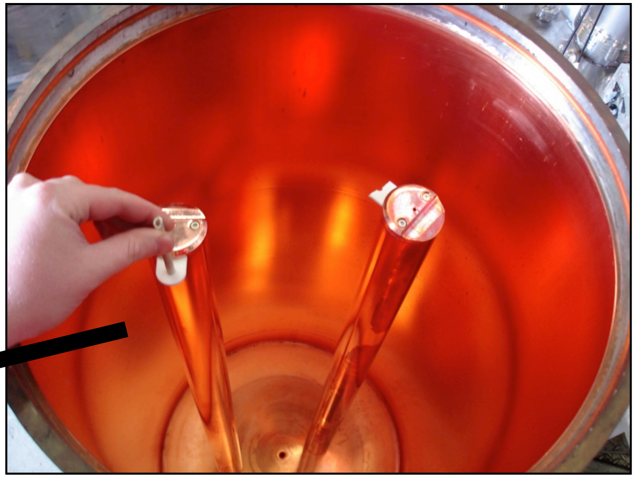
*Field compensation magnet for SQUIDs*



*11’*

*SQUID amplifier*

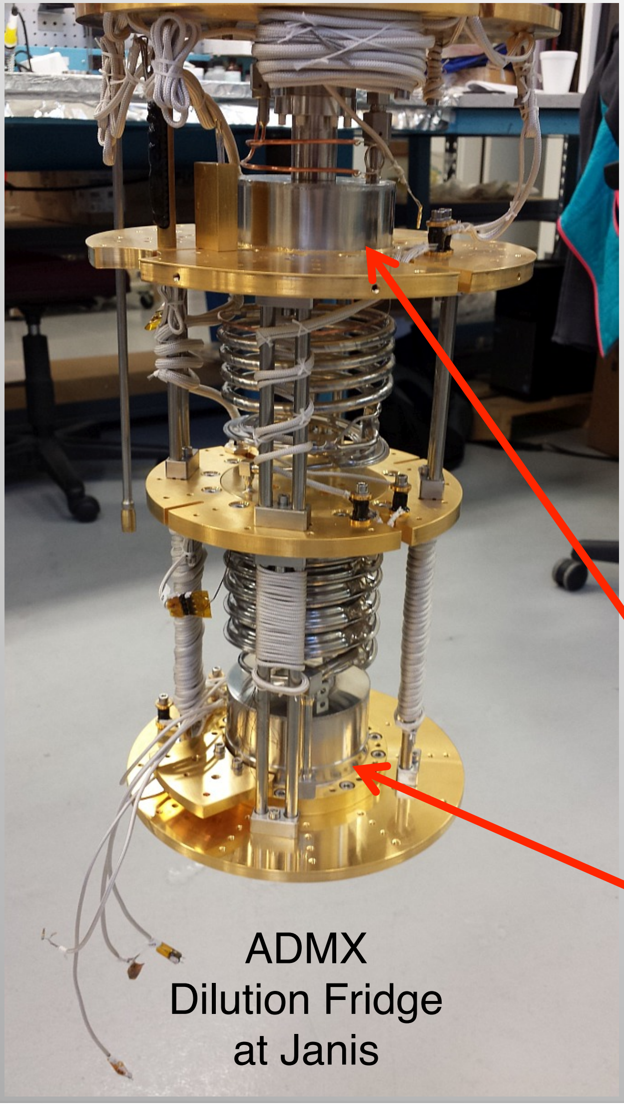


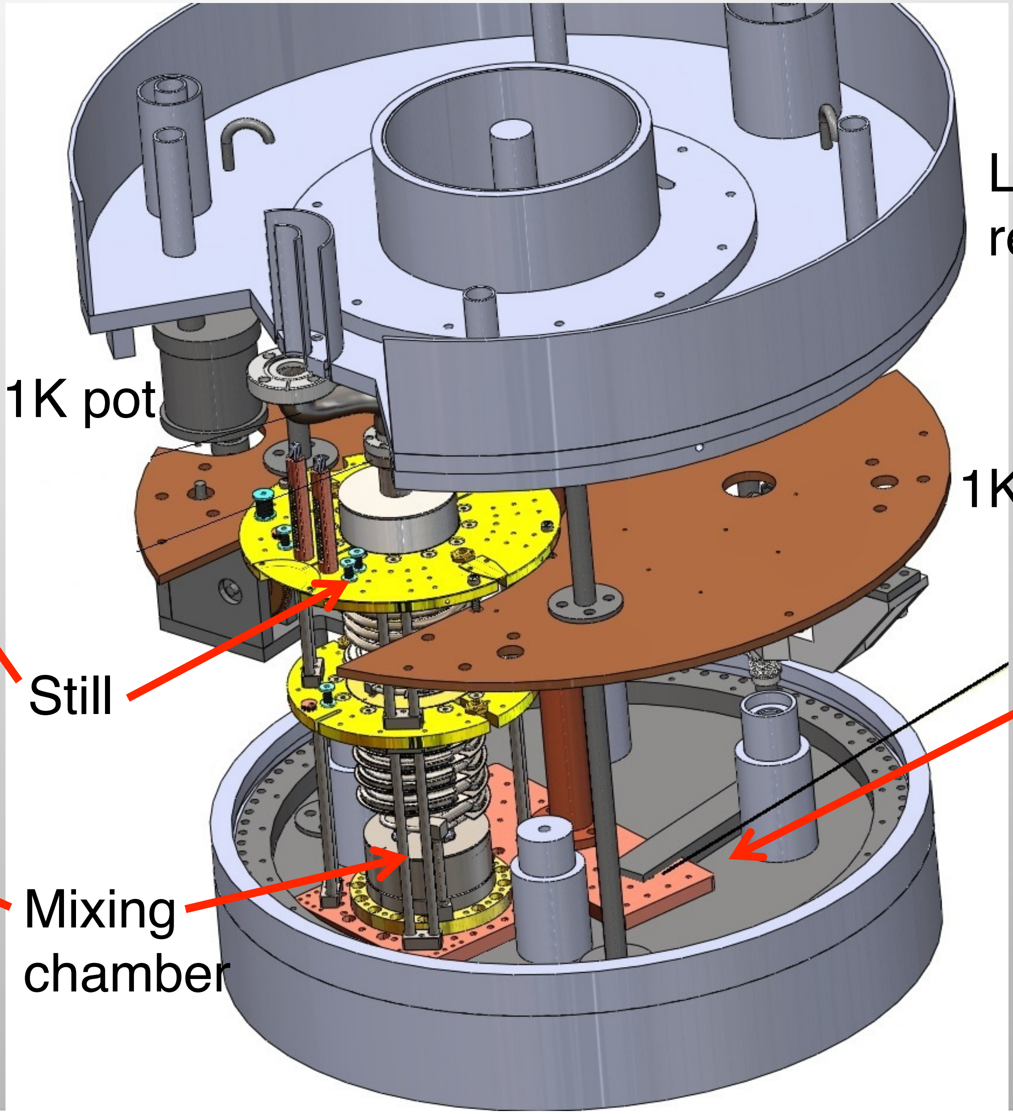



*8 Tesla Magnet*

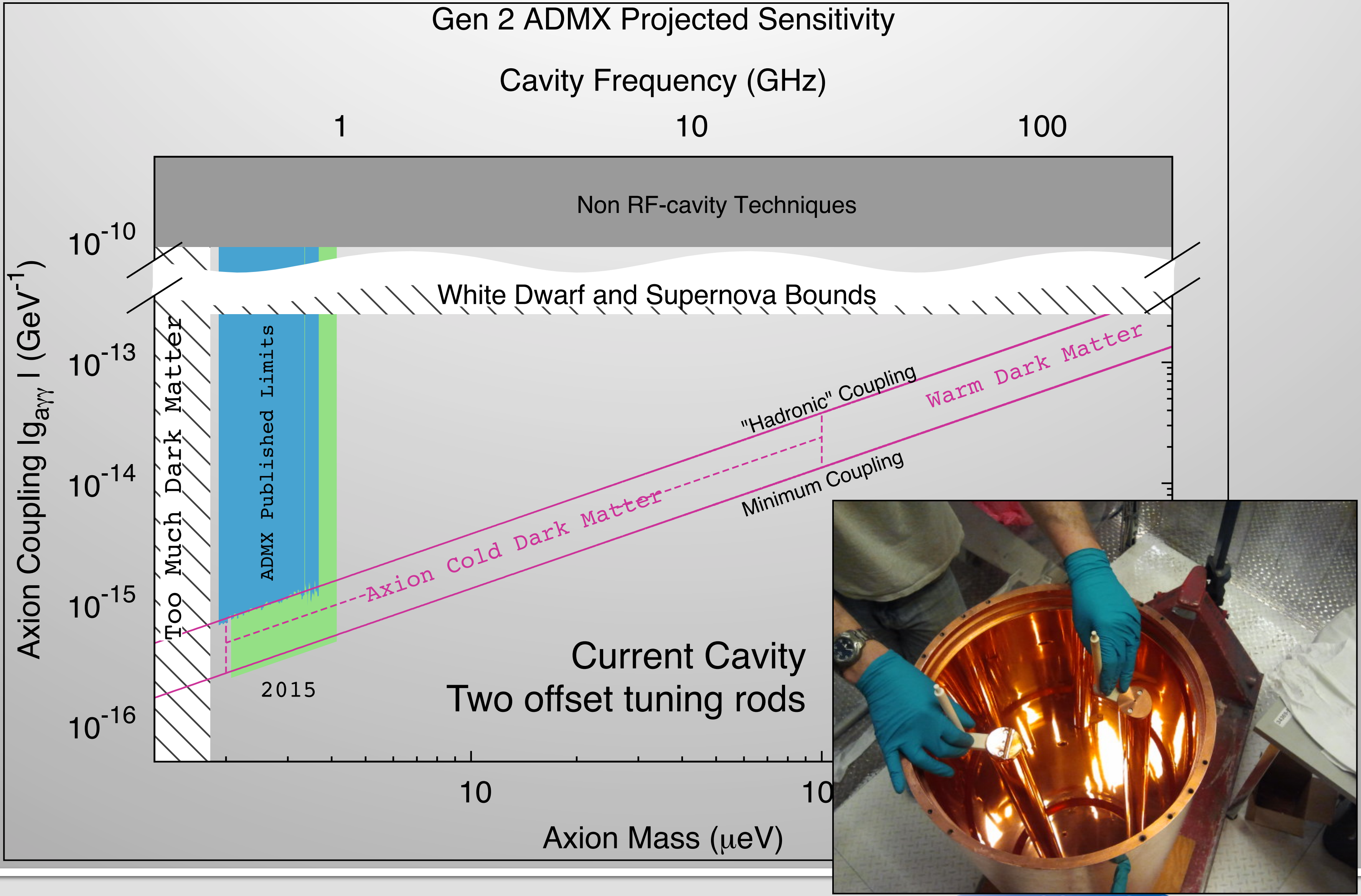
*140 liter microwave cavity (500 MHz - 1 GHz)*

# Dil. Fridge (800 μW at 100 mK) being commissioned now



# ADMX Gen 2 Science Prospects: Year 1 (0.5 – 1 GHz)

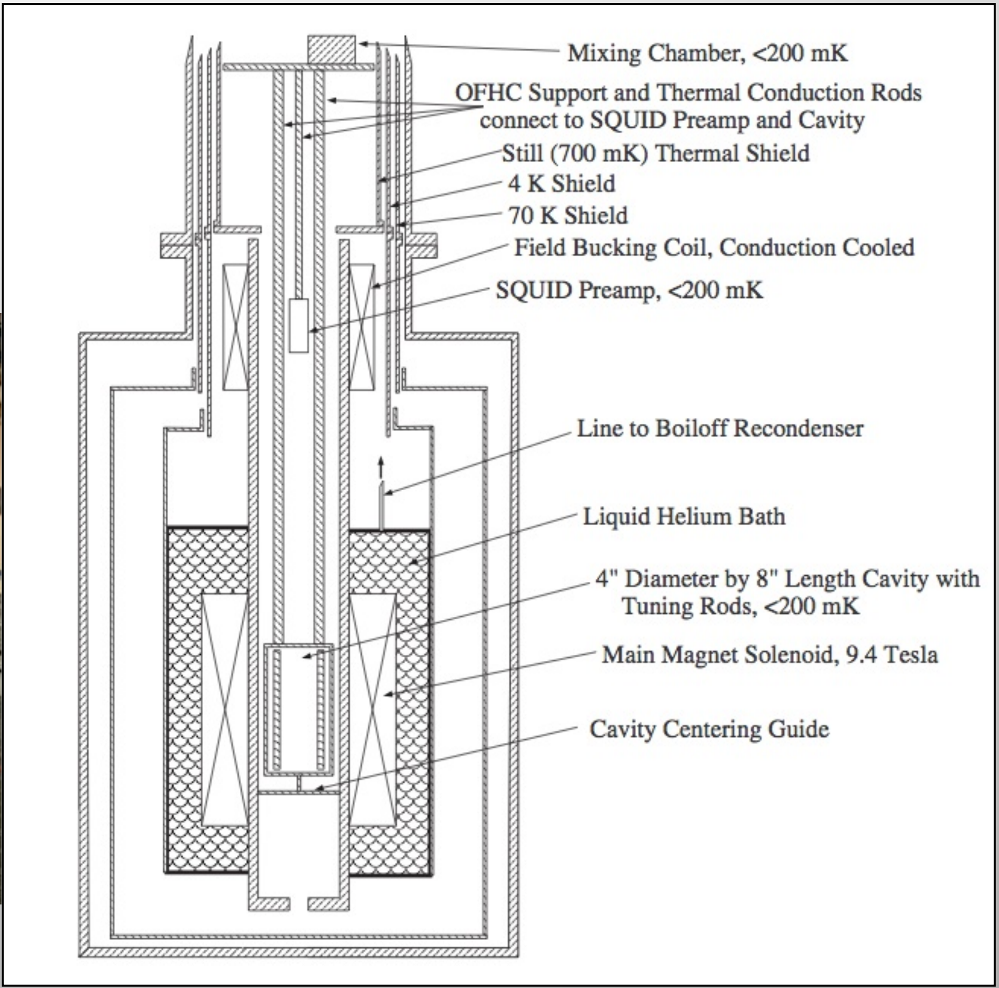


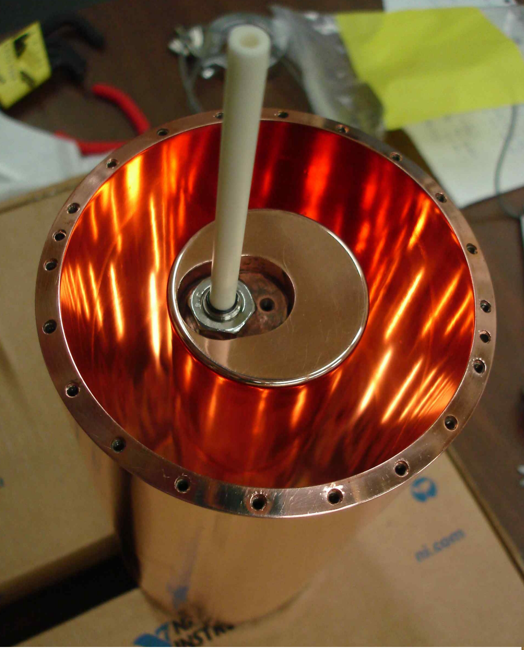
# ADMX – HF: High Frequency

**Second ADMX site: Yale University – NSF Sponsored**

**PI: Prof. Steve Lamoreaux**

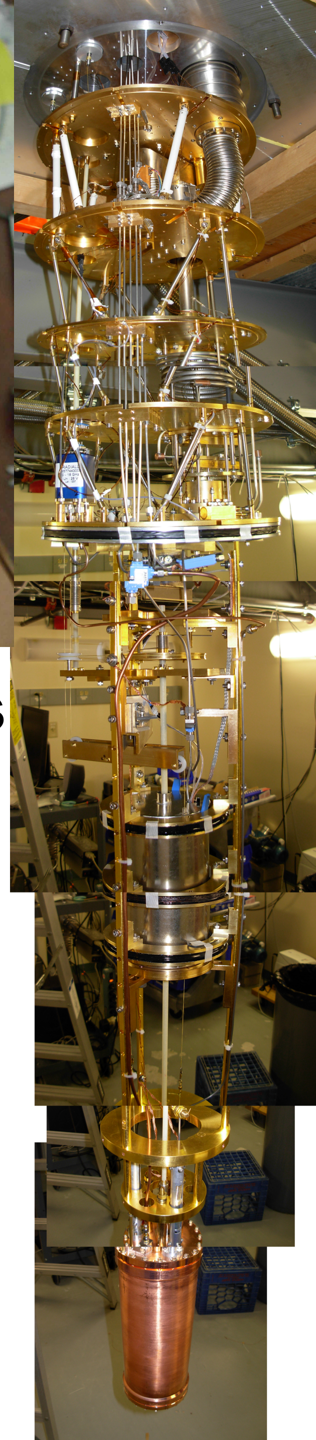
- **New Superconducting Magnet**
  **5” diameter, 20” long, 9.4 T**
- **Existing Dilution fridge.**



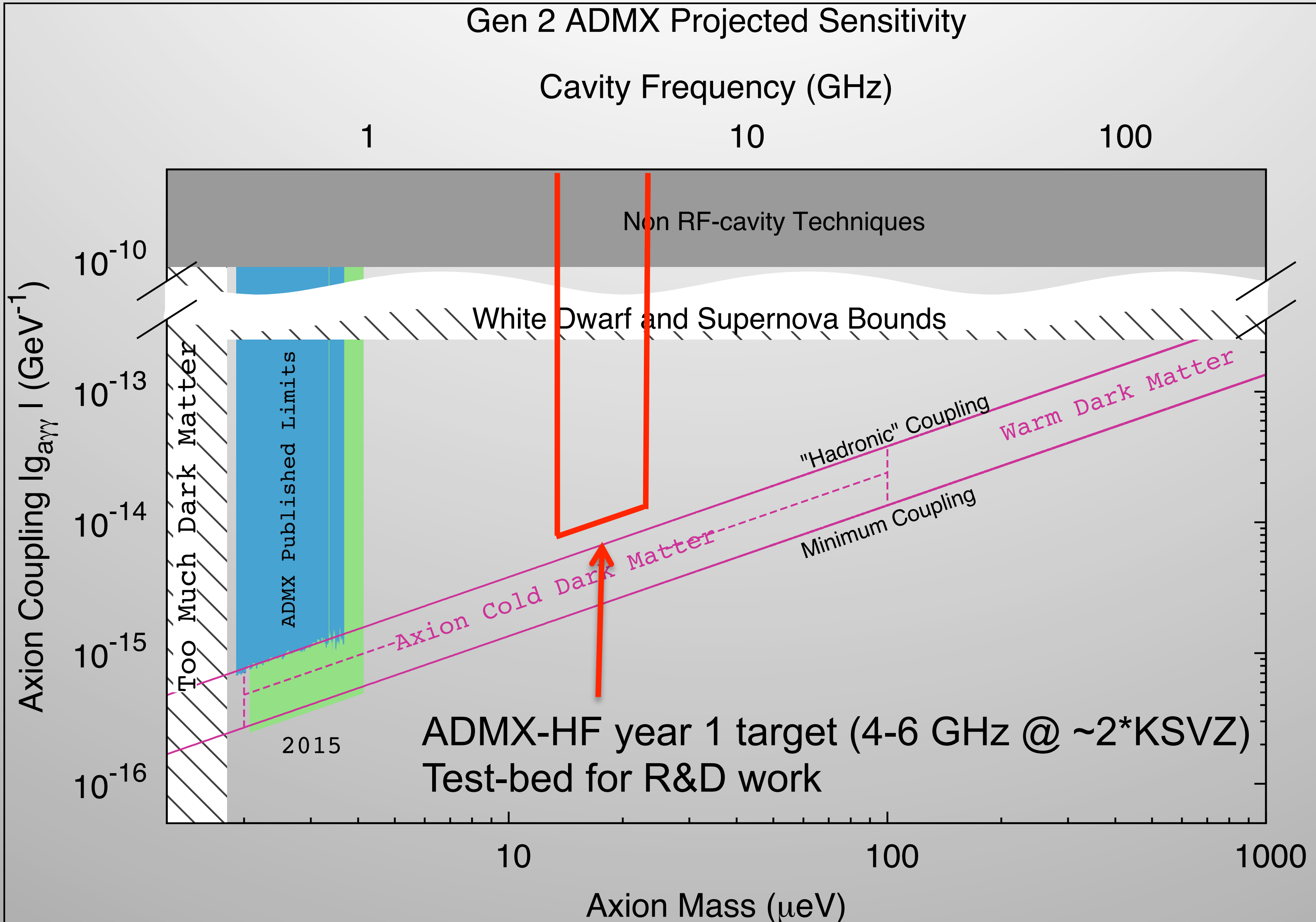


# ADMX-HF Status

- Construction 2012-15
- Cavity volume ~ 1% that of ADMX
- 48 MHz run performed at $T_{SYS} \sim 2.5\ T_{SQL}$
- Long run begins fall 2015 in > 5 GHz range



# ADMX-HF: Year 1 prospects



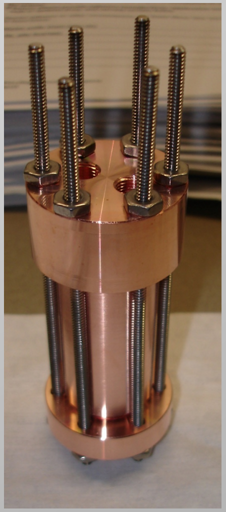
# Challenges for cavities at higher frequencies/mass

- Higher Frequency requires smaller cavities – sample smaller volume!
- Quality factor goes down as frequency increases!

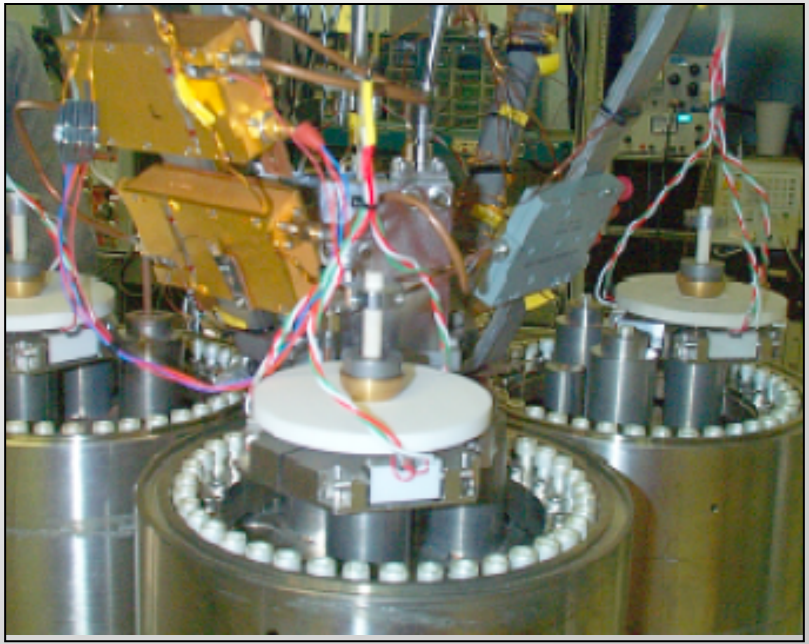
**Radius – 19 inches**
**Frequency ~ 540 MHz**
**Q – 200,000**
**Axion Mass ~ 2 μeV**
**Volume – 220 liters**

**Radius – 2.5 inches**
**Frequency ~ 2.4 GHz**
**Axion Mass ~ 9 μeV**
**Q – 120,000**
**Volume ~ 2.6 liters**

**Radius – 0.5 inches**
**Frequency ~ 10 GHz**
**Axion Mass ~ 36 μeV**
**Q – 50,000**
**Volume – 0.025 liters**



# ADMX Gen2: Cavities for higher frequencies



**Larger sets of tuning rods in current cavity**

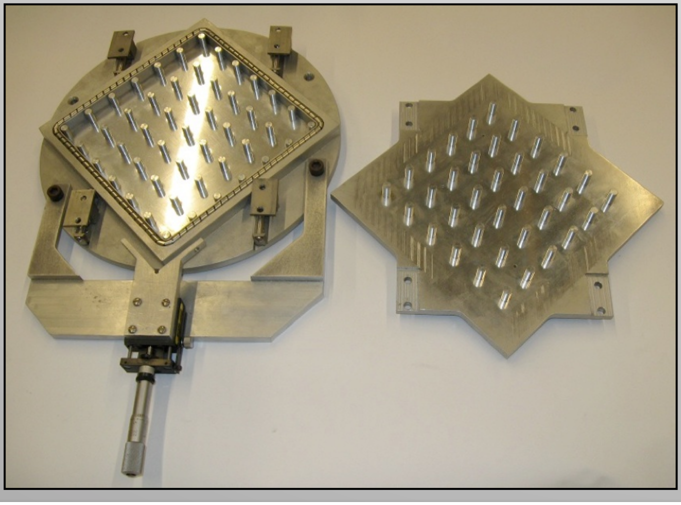
- Good to ~ 2 GHz (Q ~ $10^5$ / Vol ~ 100 l)

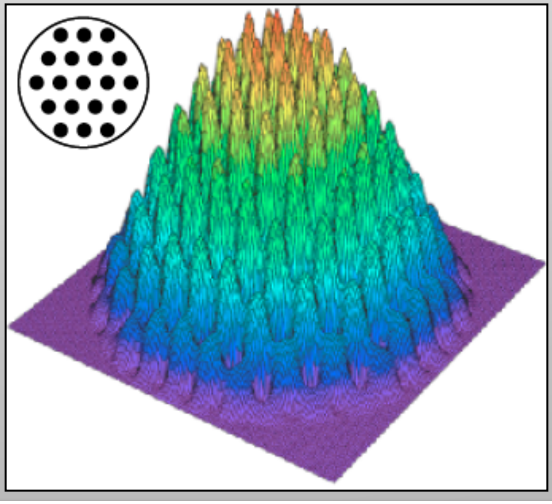
**Multiple cavities in magnet bore**

- Possible to use up to ~ 3 – 4 GHz
- Difficult to scale to > 8 cavities

**Photonic Bandgap Cavities**

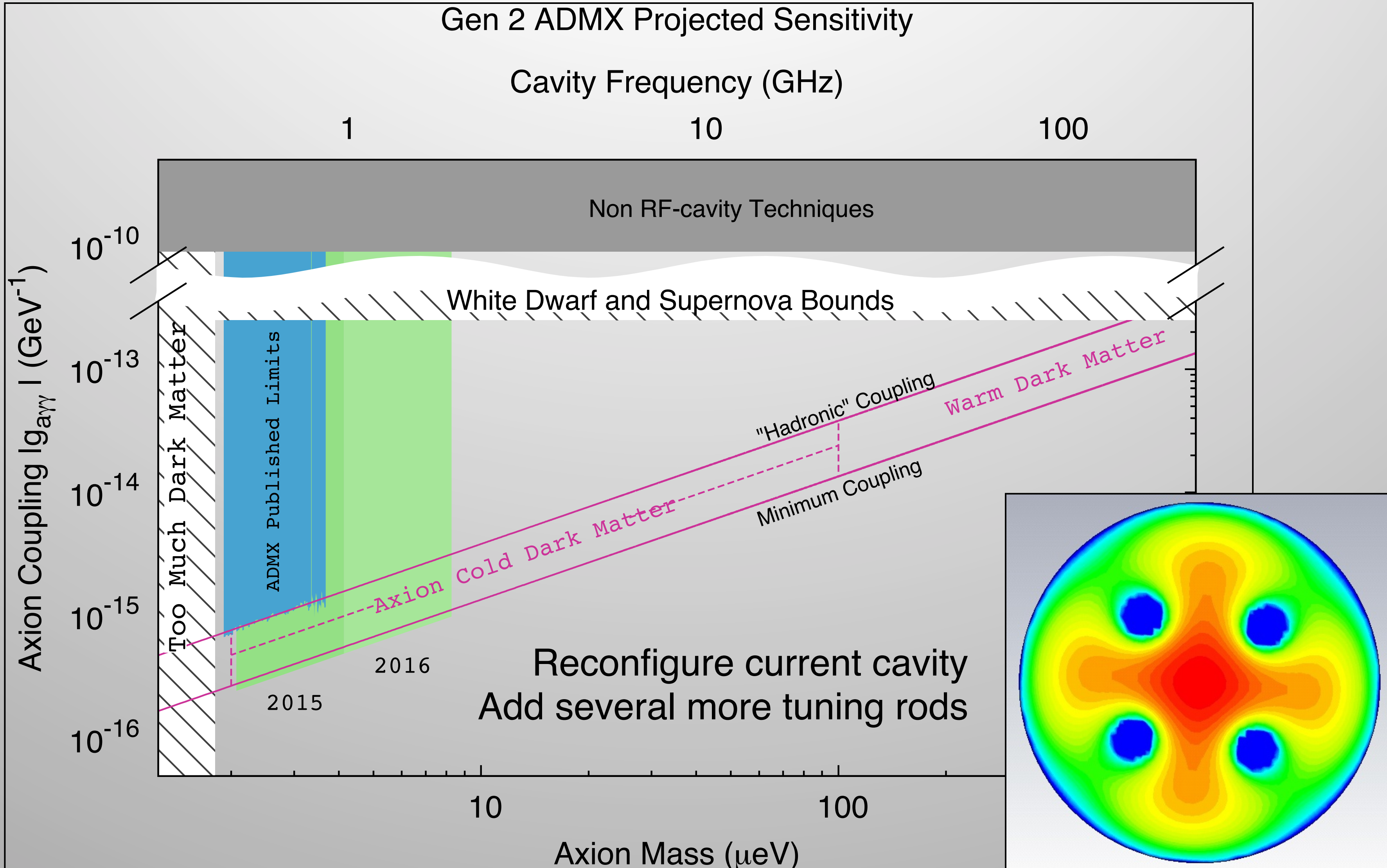
- Lattice of posts for higher frequencies
- Maintain relatively large E-field coverage
- Use from 4 – 10 GHz



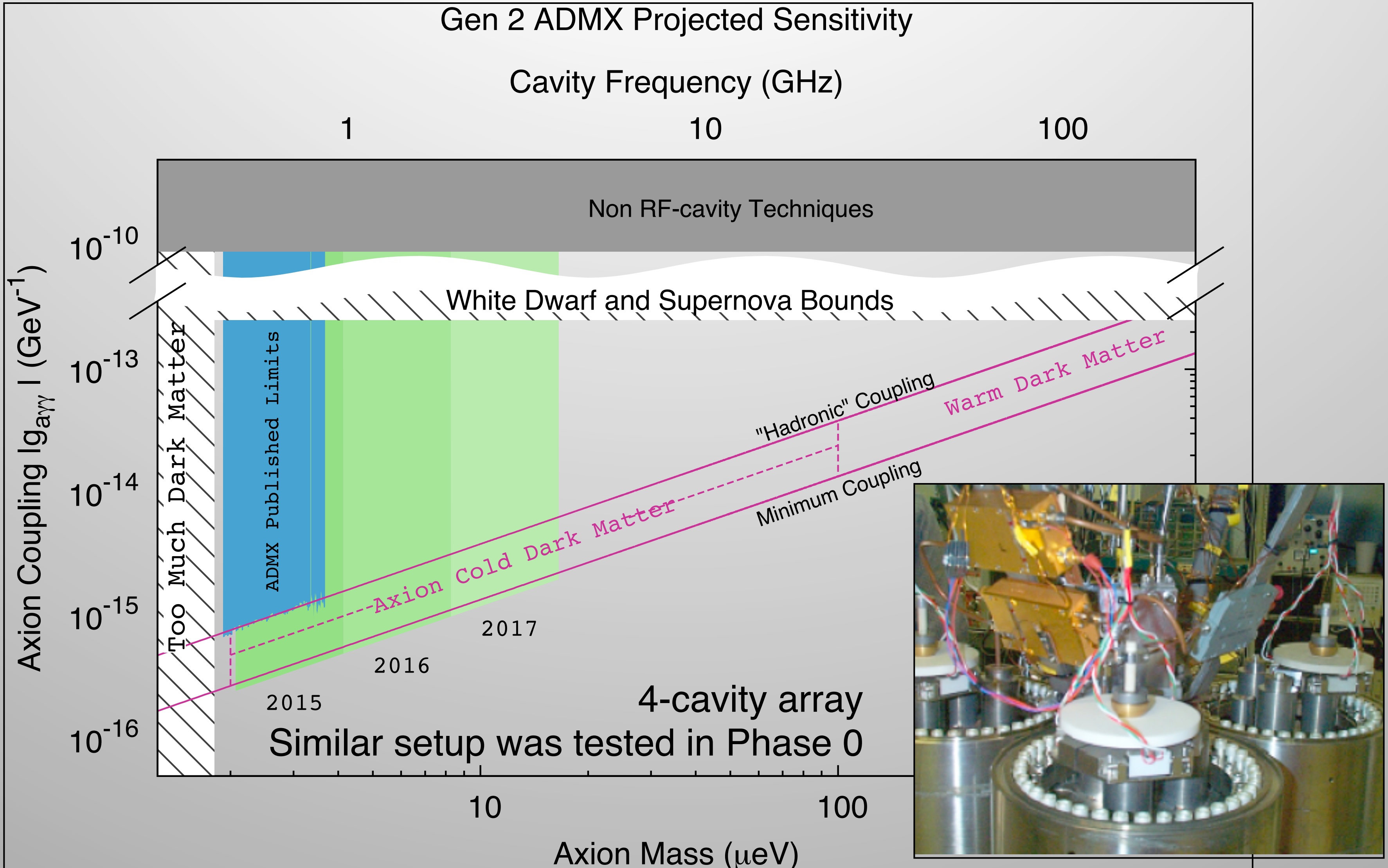


**Primary ADMX R&D focus for the next few years!**

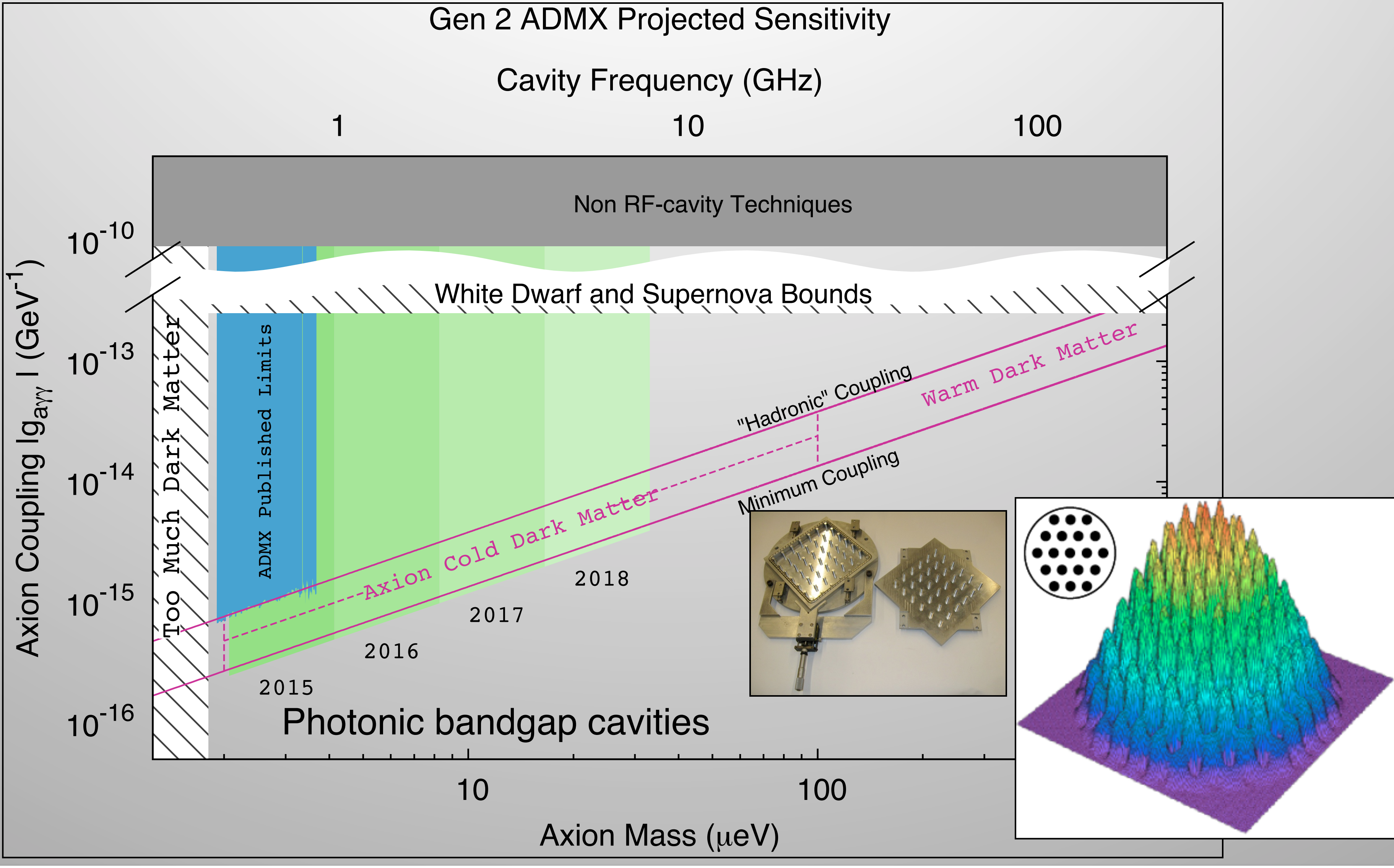
# ADMX Gen 2 Science Prospects: Year 2 (1 – 2 GHz)



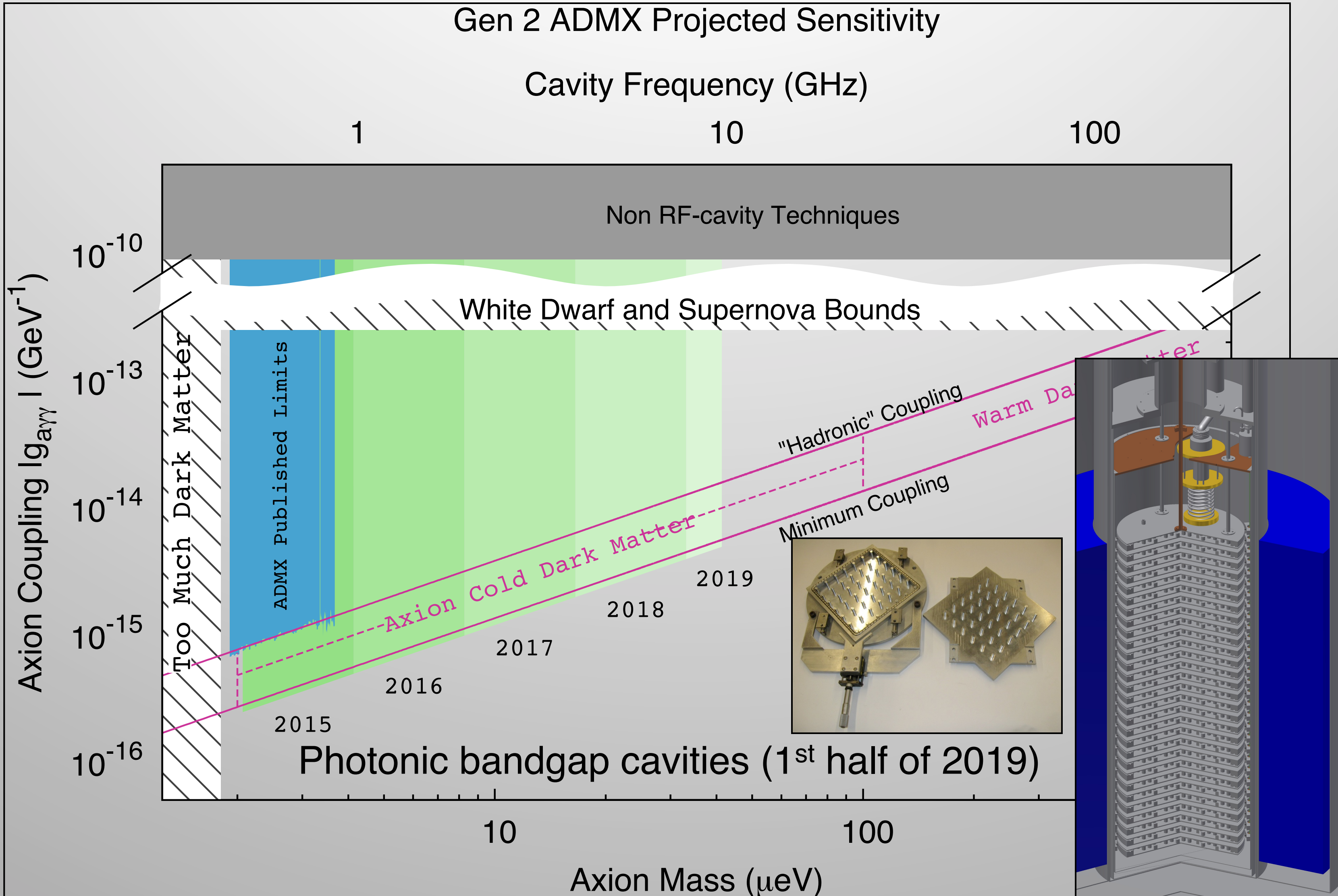
# ADMX Gen 2 Science Prospects: Year 3 (2 – 4 GHz)



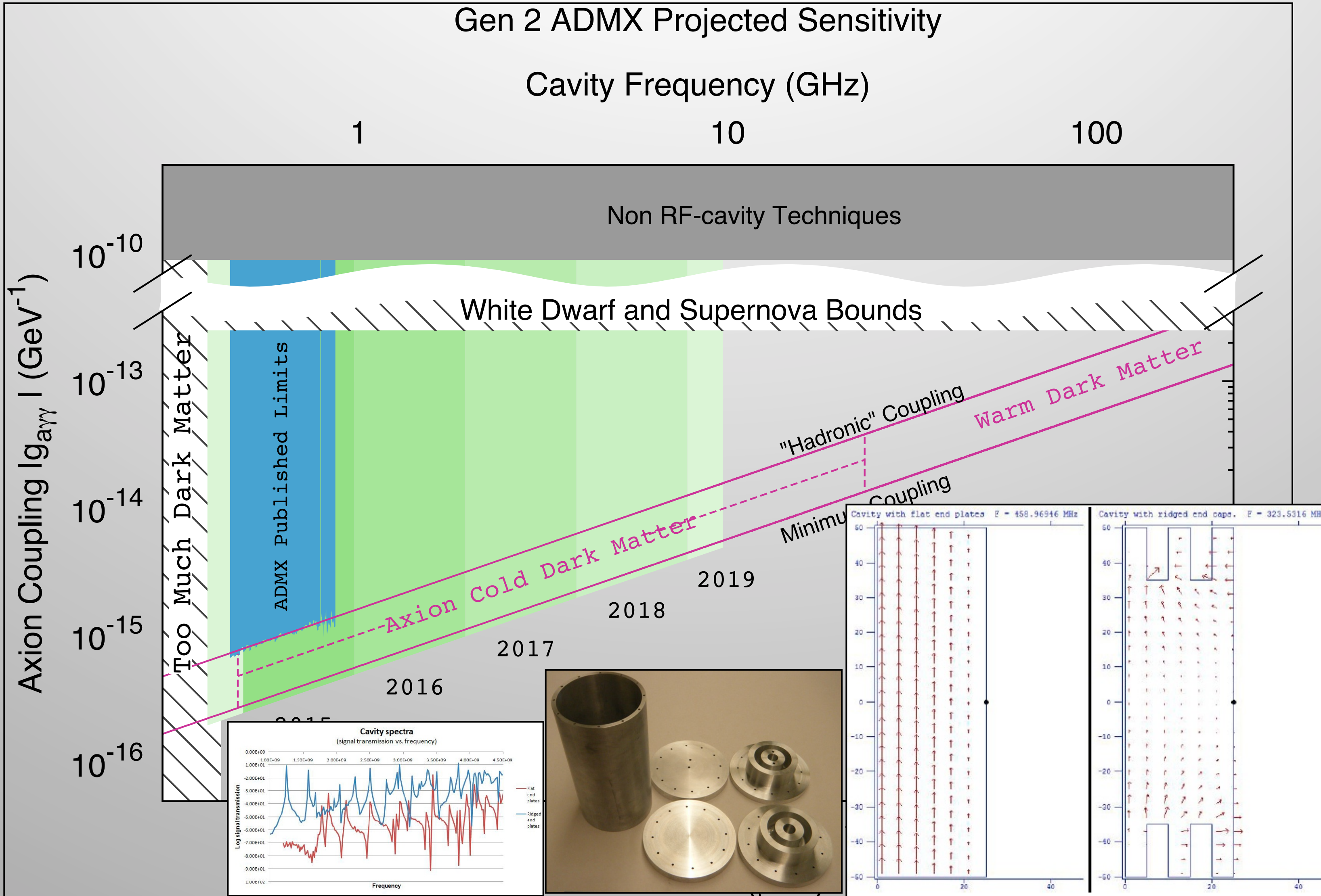
# ADMX Gen 2 Science Prospects: Year 4 (4 – 8 GHz)



# ADMX Gen 2 Science Prospects: Year 5 (8 – 10 GHz)

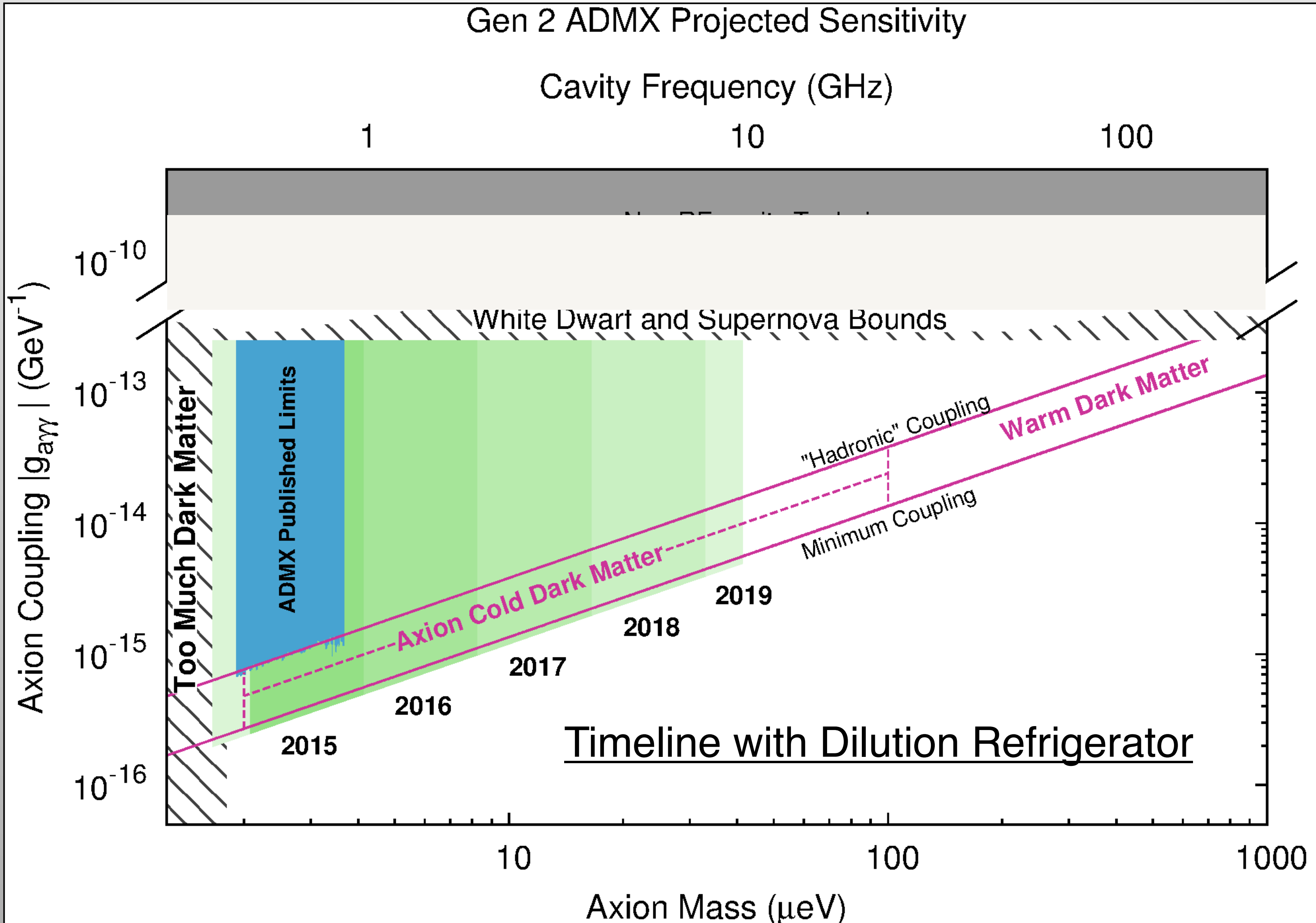


# ADMX Gen 2 Science Prospects: Year 5 ( < 0.5 GHz)




Slow-wave cavity
(2nd half of 2019)

# Quantum Limited Amplifers



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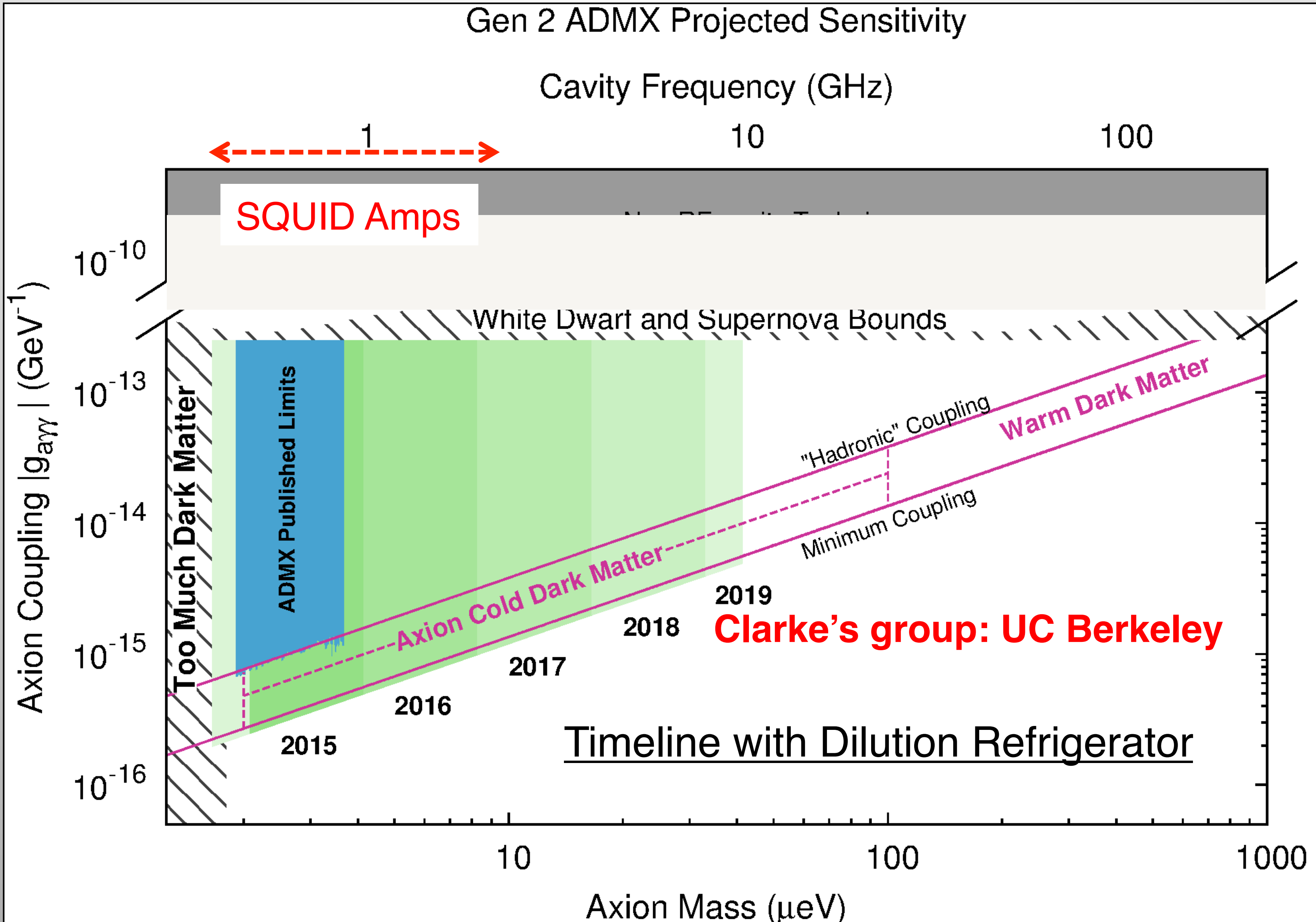

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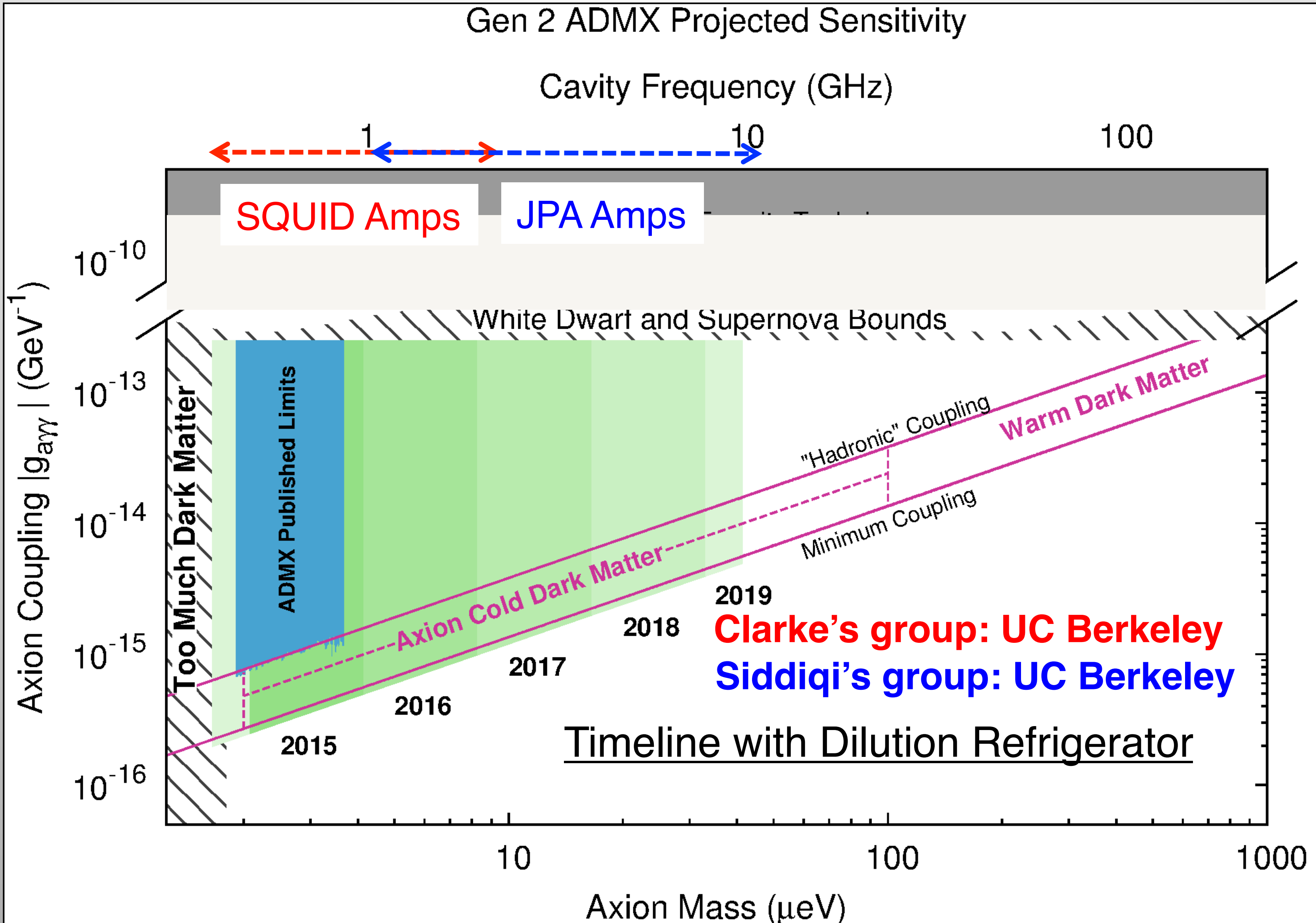


# Going beyond the (relatively) near term searches…

# New Magnet Systems: Maximize $B^2V$

- Magnet technology continues to improve
- Large solenoid fields (> 22 T) now possible
- Scan Rate ~ $B^4V^2$
- Prudent to invest here to broaden search
- Multiple frequencies scanned at same time

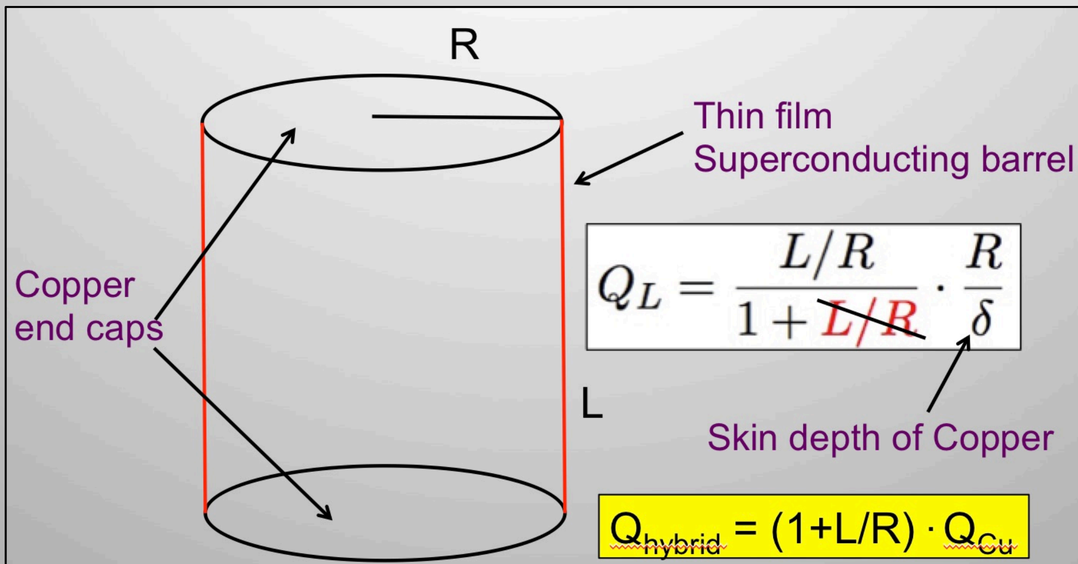
Bruker NMR magnet
23.5 T with 5.4 cm bore


ADMX magnet
8 T with 0.5 m bore

# Microwave Cavity Challenges

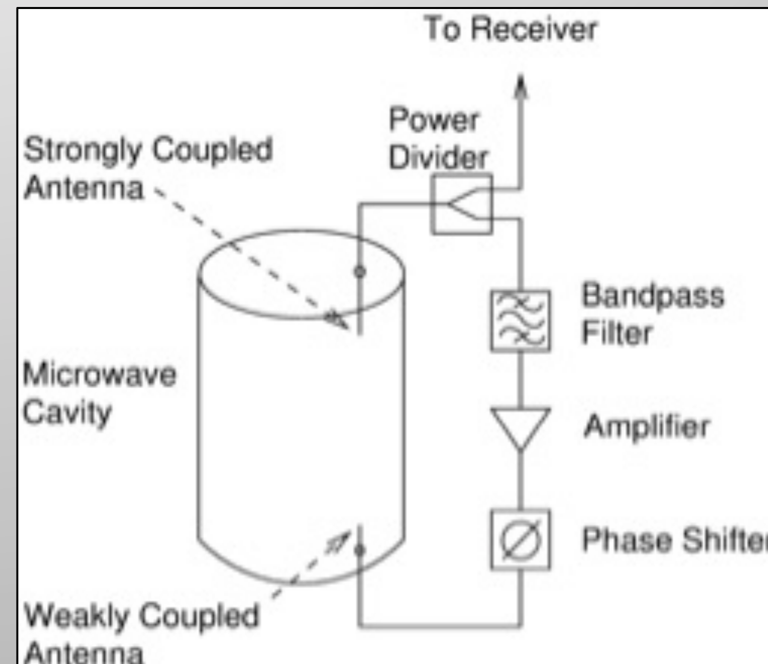
- Maximize Volume inside B-Field ($P_a \propto B^2V$)
- Maximize Form Factor: $$C_{lmn} = \frac{|\int_V d^3x \vec{E}_\omega \cdot \vec{B}_0|^2}{B_0^2 V \int_V d^3x \epsilon |\vec{E}_\omega|^2}$$
- Maximize Quality Factor (up to $Q_a \sim 10^6$)

Superconducting "hybrid" cavities



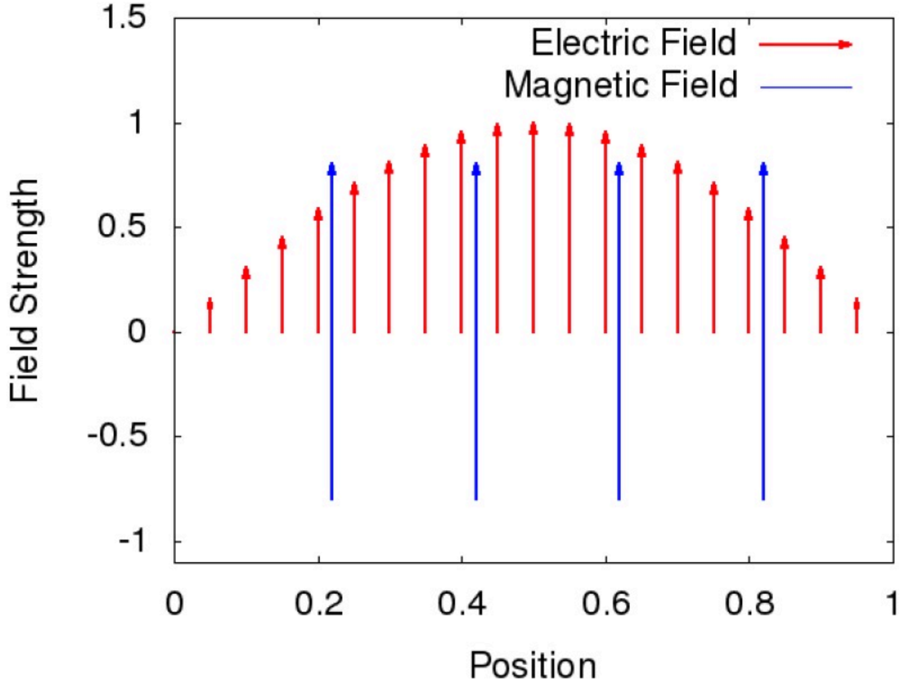

Leverage superconducting acc. cavity development

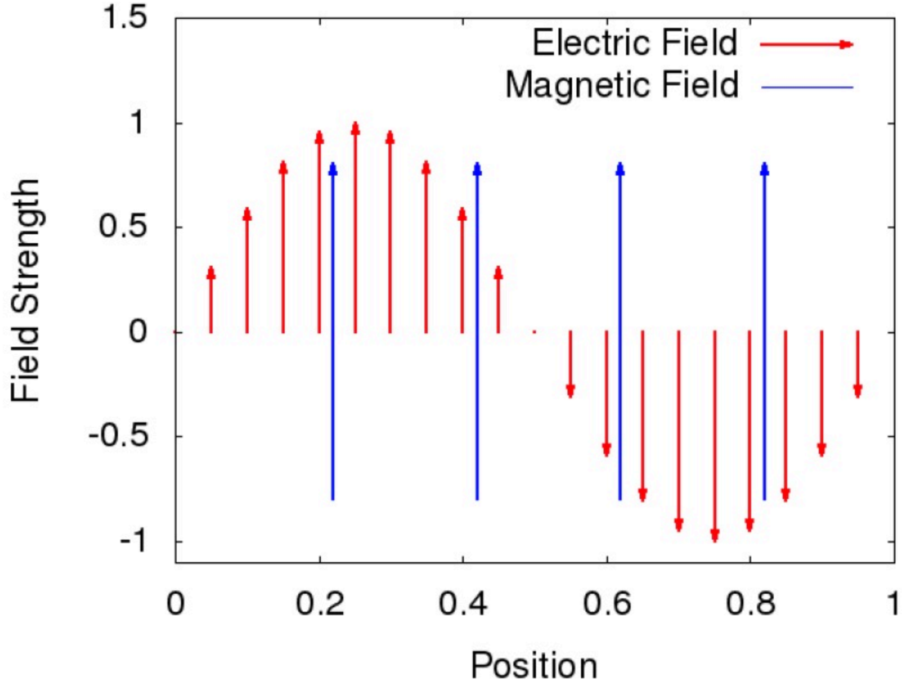
Active Feedback Cavities



# New Geometries: beyond cylinder in solenoid

Q decreases with increasing frequency, and volume decreases with wavelength in a constant magnetic field



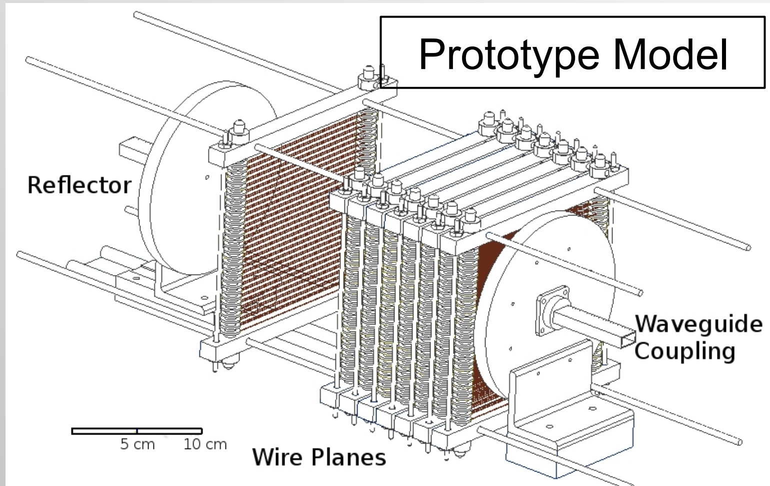



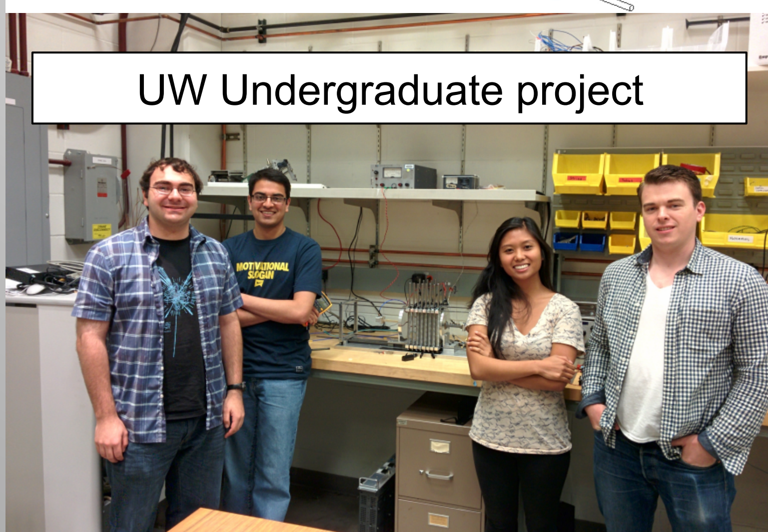

This mode couples to axions.
(Form Factor 0.8)

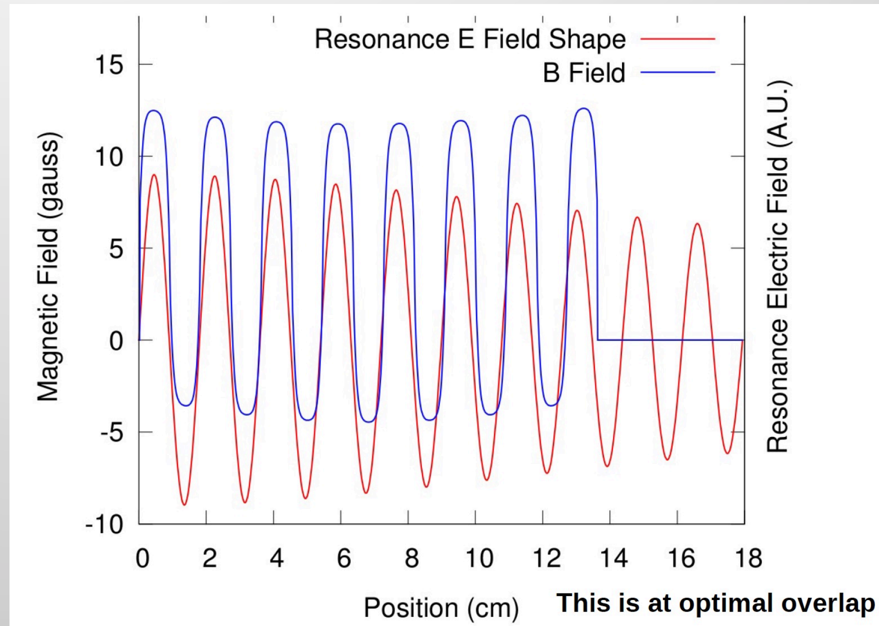
This mode does not.
(Form Factor 0)

# New Geometries: Open Resonator R&D

Open resonators may access frequencies too high to reach with closed cavities could expand ADMX reach to highest possible dark matter axion masses




PhysRevD.91.011701

System potentially good to much higher frequencies (40 GHz or more)

# Open Resonator R&D

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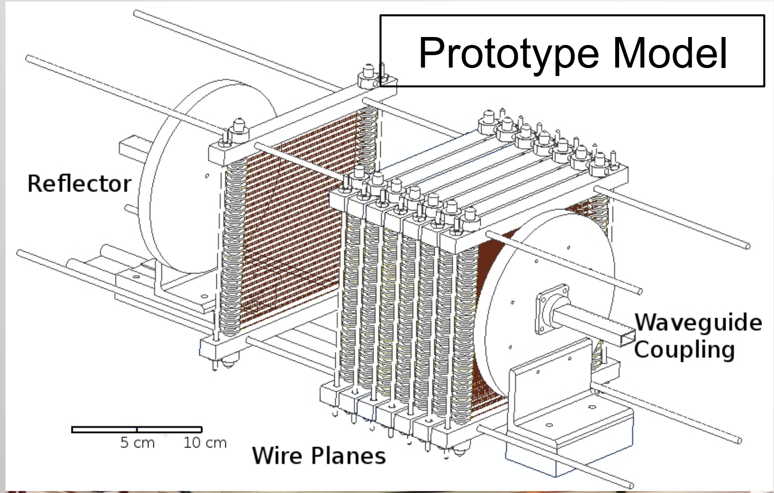


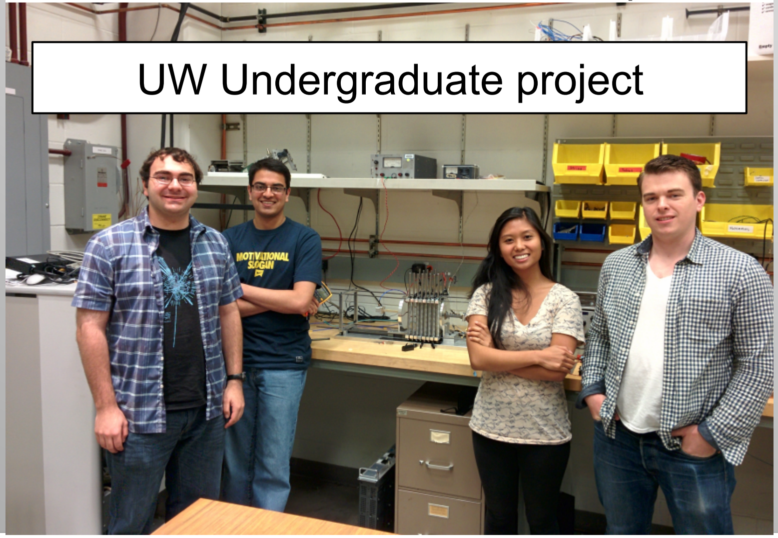


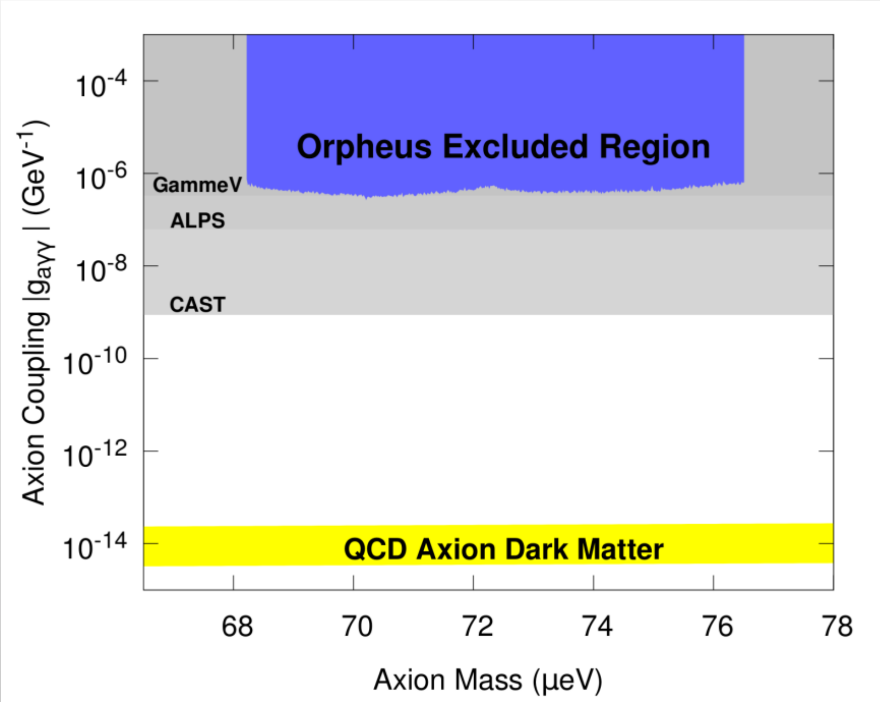


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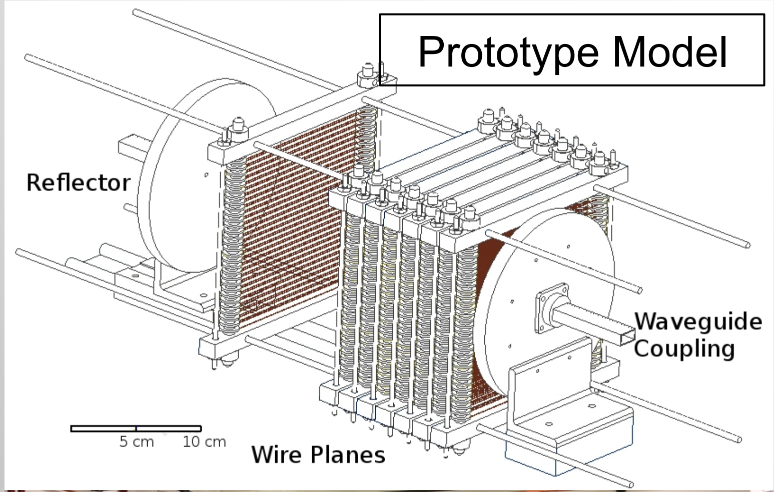


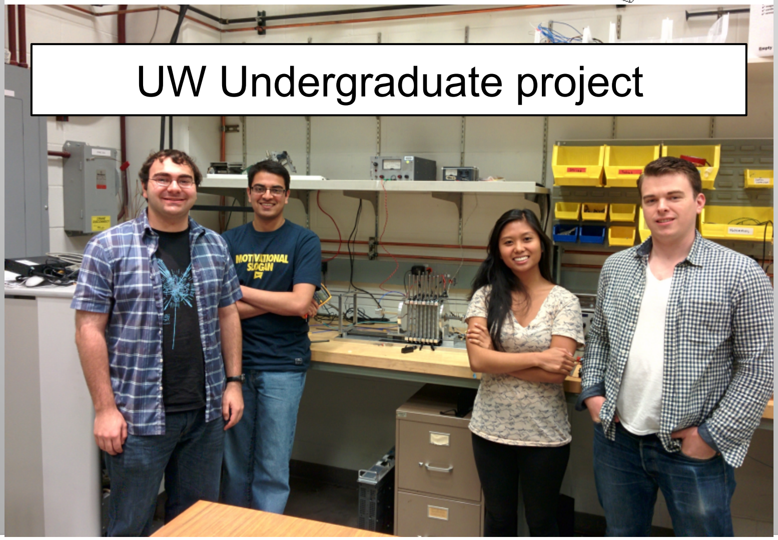


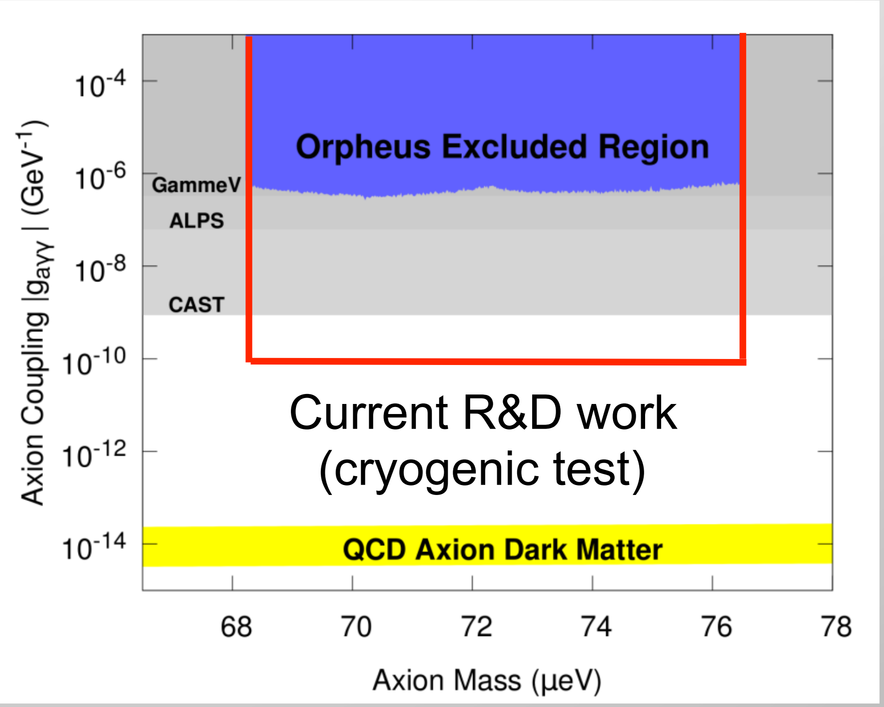


PhysRevD.91.011701

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# Linear amplifiers are subject to the Standard Quantum Limit

$$T_N > T_{SQL} \quad \text{where} \quad k_B T_{SQL} = h\nu$$

| $\nu$ [ GHz ] | $m_a$ [ $\mu$eV ] | $T_{SQL}$ [ mK ] |
|---|---|---|
| 0.5 | 2.1 | 24 |
| 5 | 20.7 | 240 |
| 20 | 82.8 | 960 |

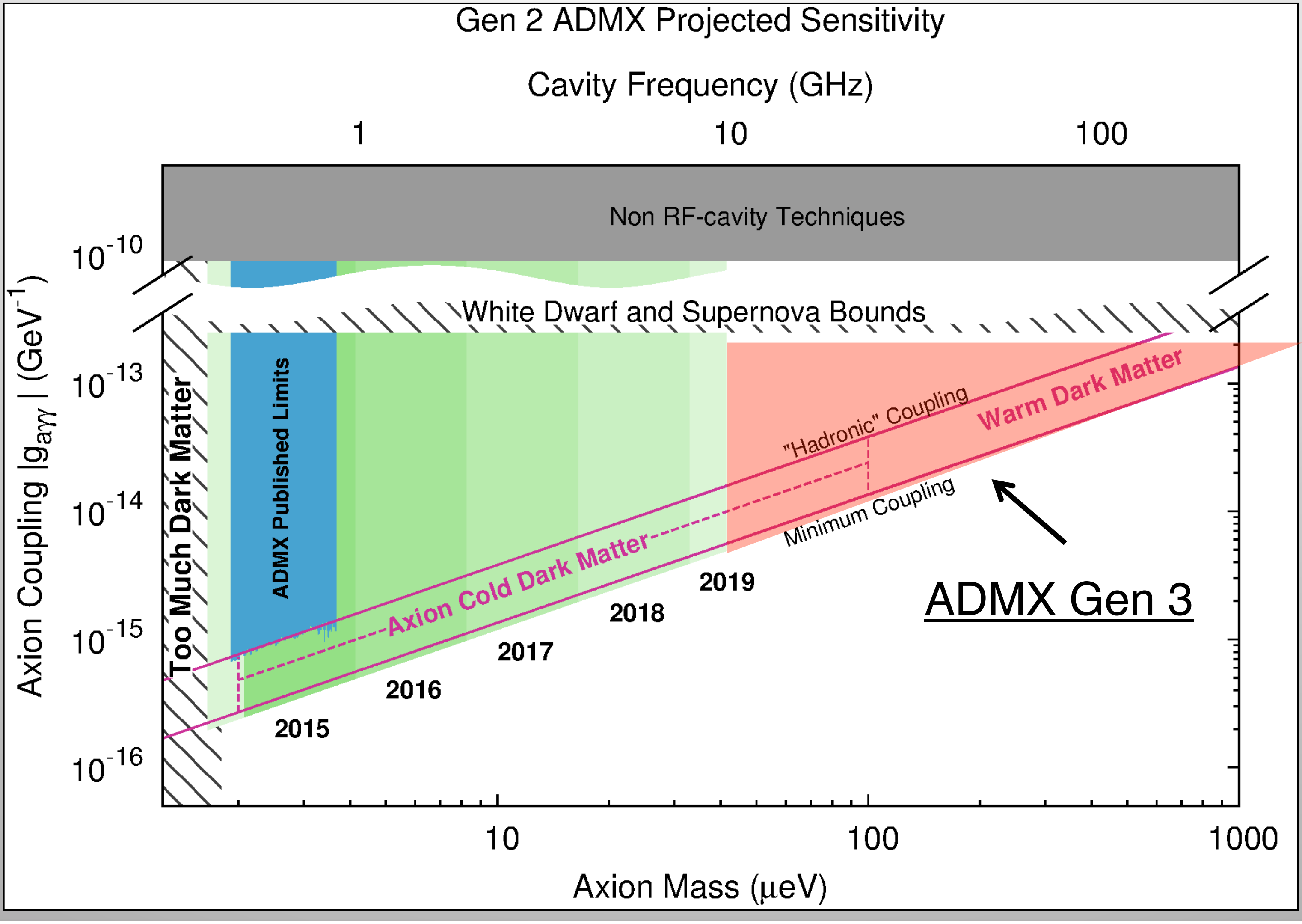
The SQL can be evaded by:

- Squeezed-vacuum state receiver (e.g. GEO, LIGO)
- Single-photon detectors (e.g. qubits, bolometers)

* S.K. Lamoreaux et al. (PhysRevD.88.035020)

# ADMX Generation 3

Long term goal is to detect or rule out axion as primary dark matter candidate.

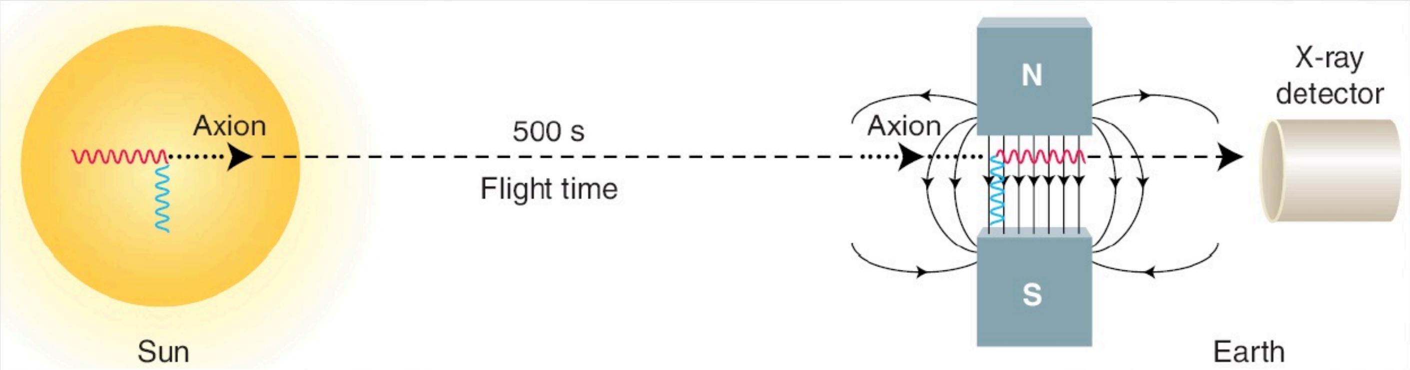


# Production and detection of axions

- First axion helioscope proposed by P. Sikivie

Sikivie *PRL* 51:1415 (1983)

  - Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagentic fields in the plasma
  - Reconversion of axions into x-ray photons is possible in strong laboratory magnetic fields

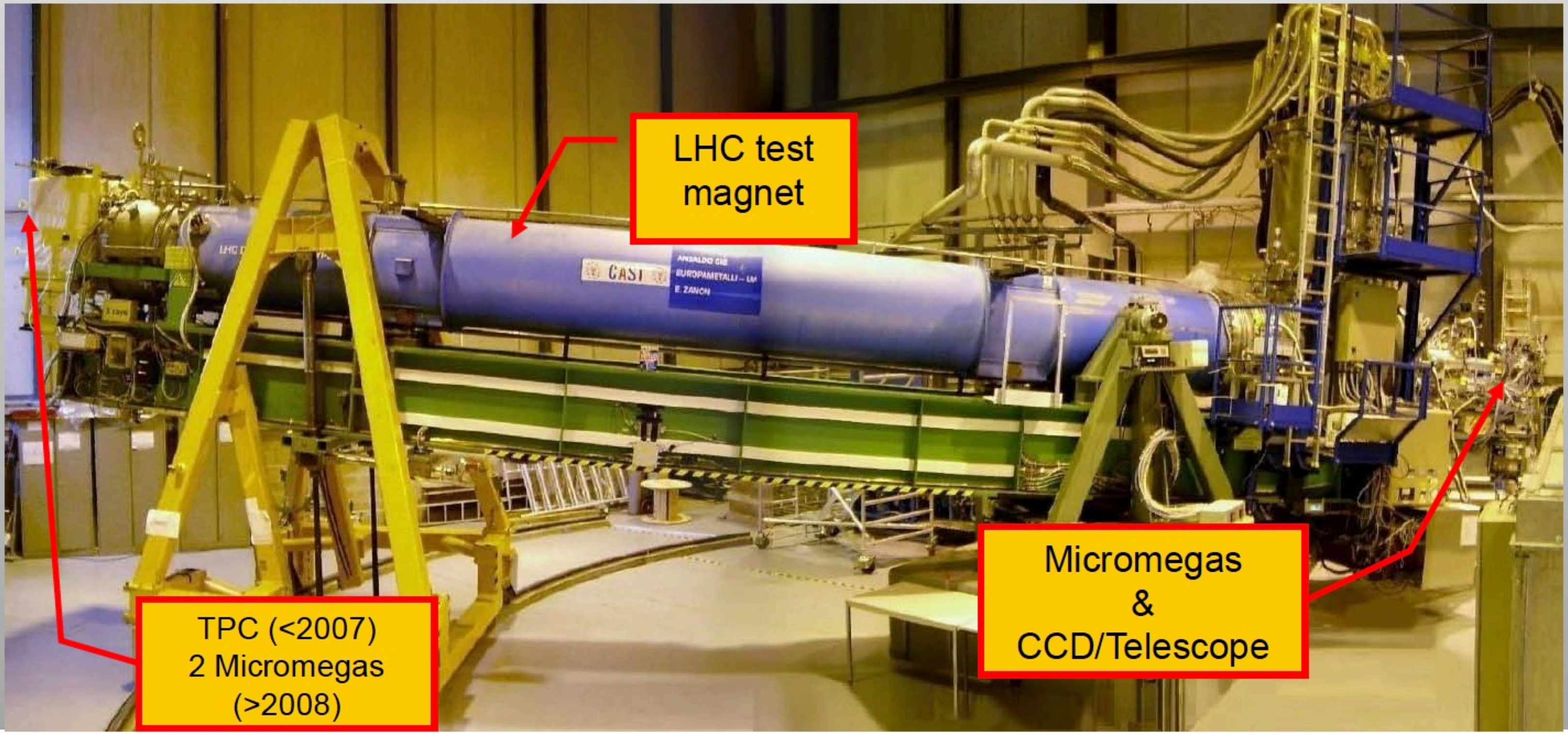



- Idea refined by K. van Bibber et al. by using buffer gas to restore coherence over long magnetic field

Van Bibber et al. *PhysRevD* 39:2089 (1989)

# CAST experiment @ CERN

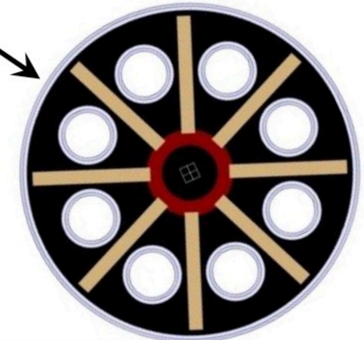
- International collaboration started in 1999
- Almost continuously acquired data since 2003
- 20 institutions from 11 countries, approximately 70 PhD scientists
- Thesis project for 10 PhD students, 6 more pending
- **Very mature technology → CAST is 3rd generation helioscope**

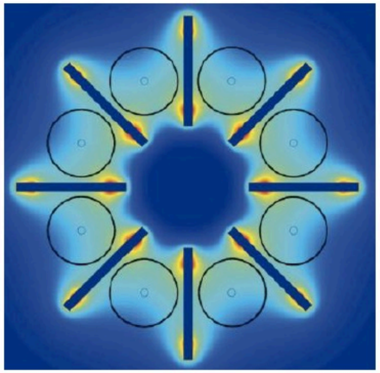


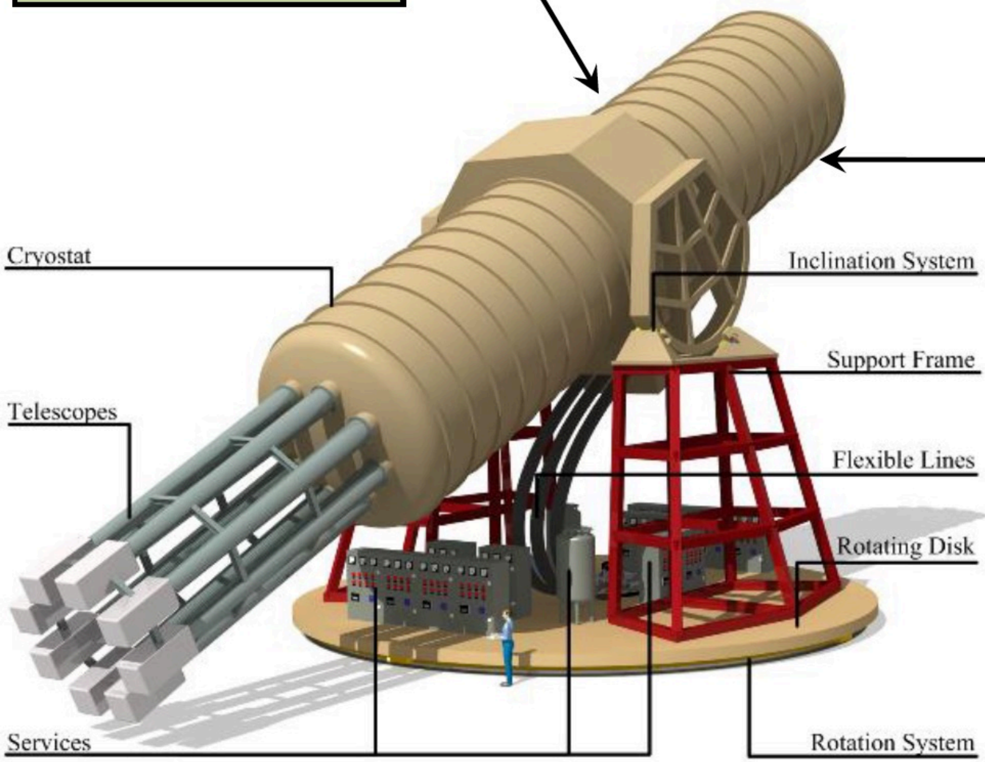
# IAXO – The new generation helioscope

**TOROIDAL CONFIGURATION specifically built for axion physics**

**Each conversion bore (between coils) 600 mm diameter**

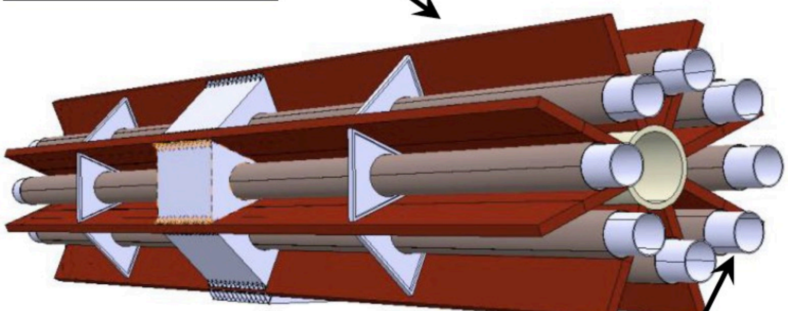







**Cryostat**

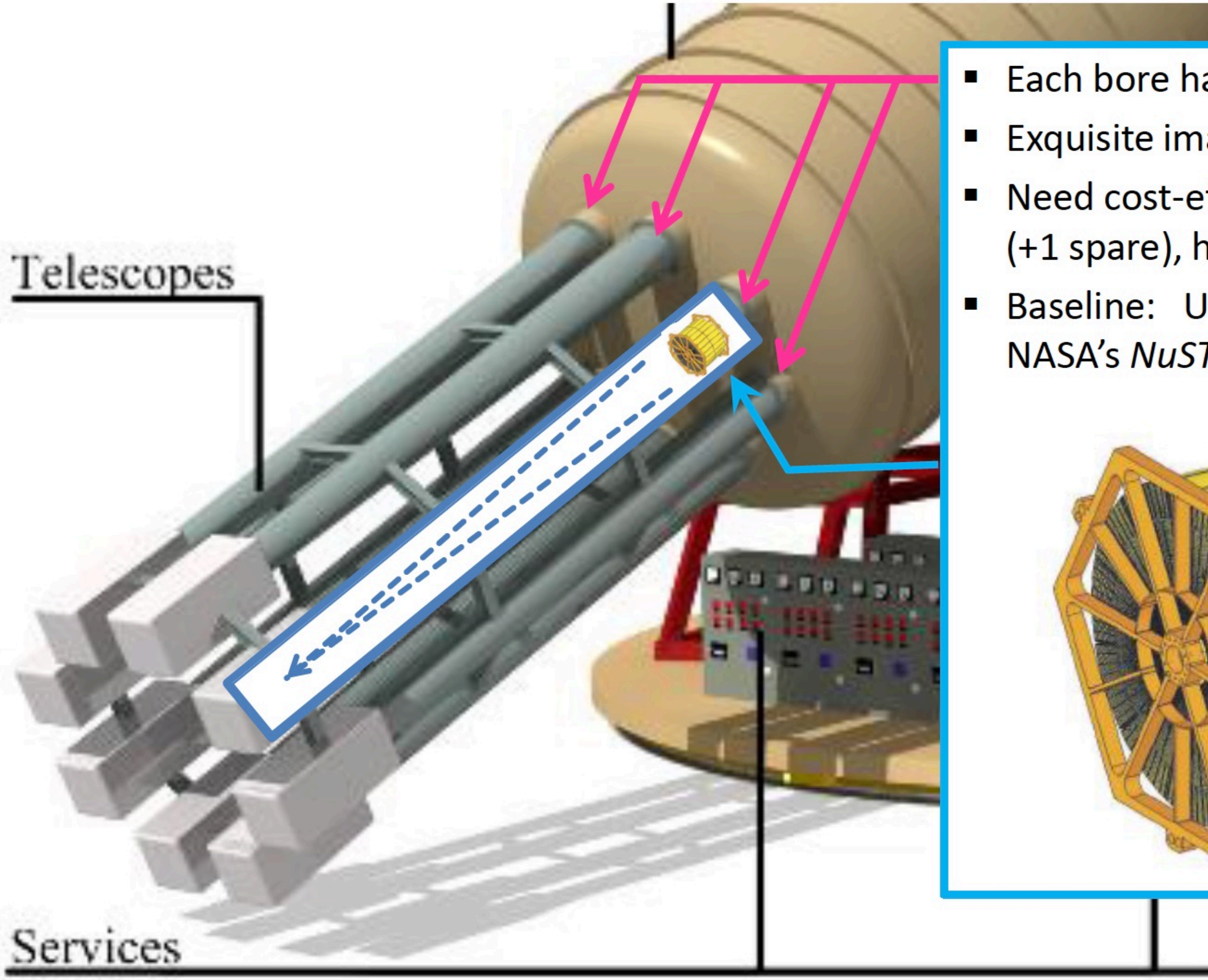
**Cold mass**



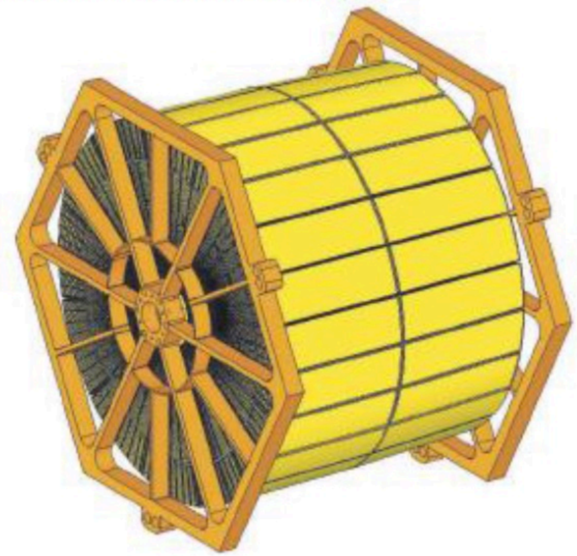
**Bores go through cryostat**

**Magnetic length 20 m    Total cryostat length 25 m**

# Solar axions energy primarily kinetic (keV X-rays)




- Each bore has an x-ray telescope
- Exquisite imaging not required
- Need cost-effective way to build 8 (+1 spare), highly nested optics
- Baseline: Use approach from NASA's *NuSTAR* satellite



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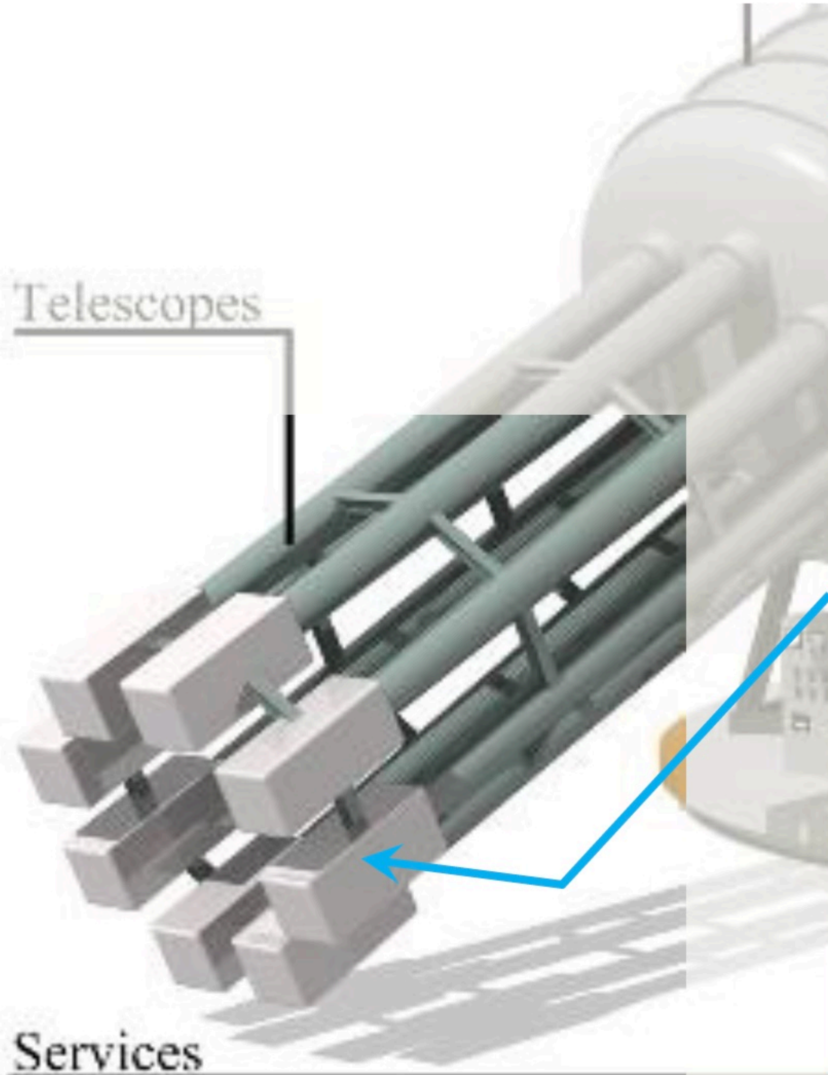
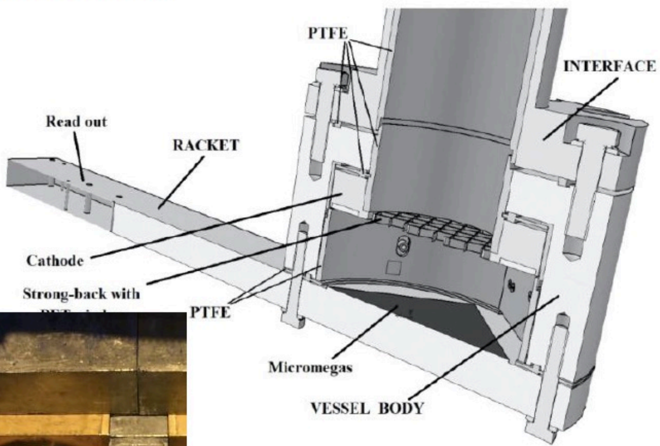
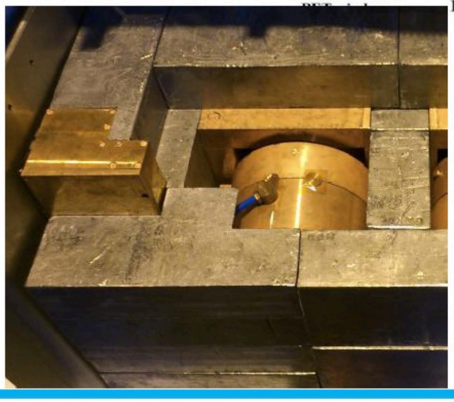



- 8 detector systems
- Small gas chamber with Micromegas readouts for low-background x-ray detection
- Optimized shielding



# Sensitivity of CAST vs IAXO

MAGNET & TRACKING

X-RAY OPTICS

X-RAY DETECTORS

$$g_{a\gamma}^4 \propto \underbrace{(BL)^{-2} A^{-1}}_{\textbf{magnet}} \times \underbrace{t^{-1/2}}_{\textbf{exposure}} \times \underbrace{s^{1/2}\varepsilon_0^{-1}}_{\textbf{optics}} \times \underbrace{b^{1/2}\varepsilon^{-1}}_{\textbf{detectors}}$$

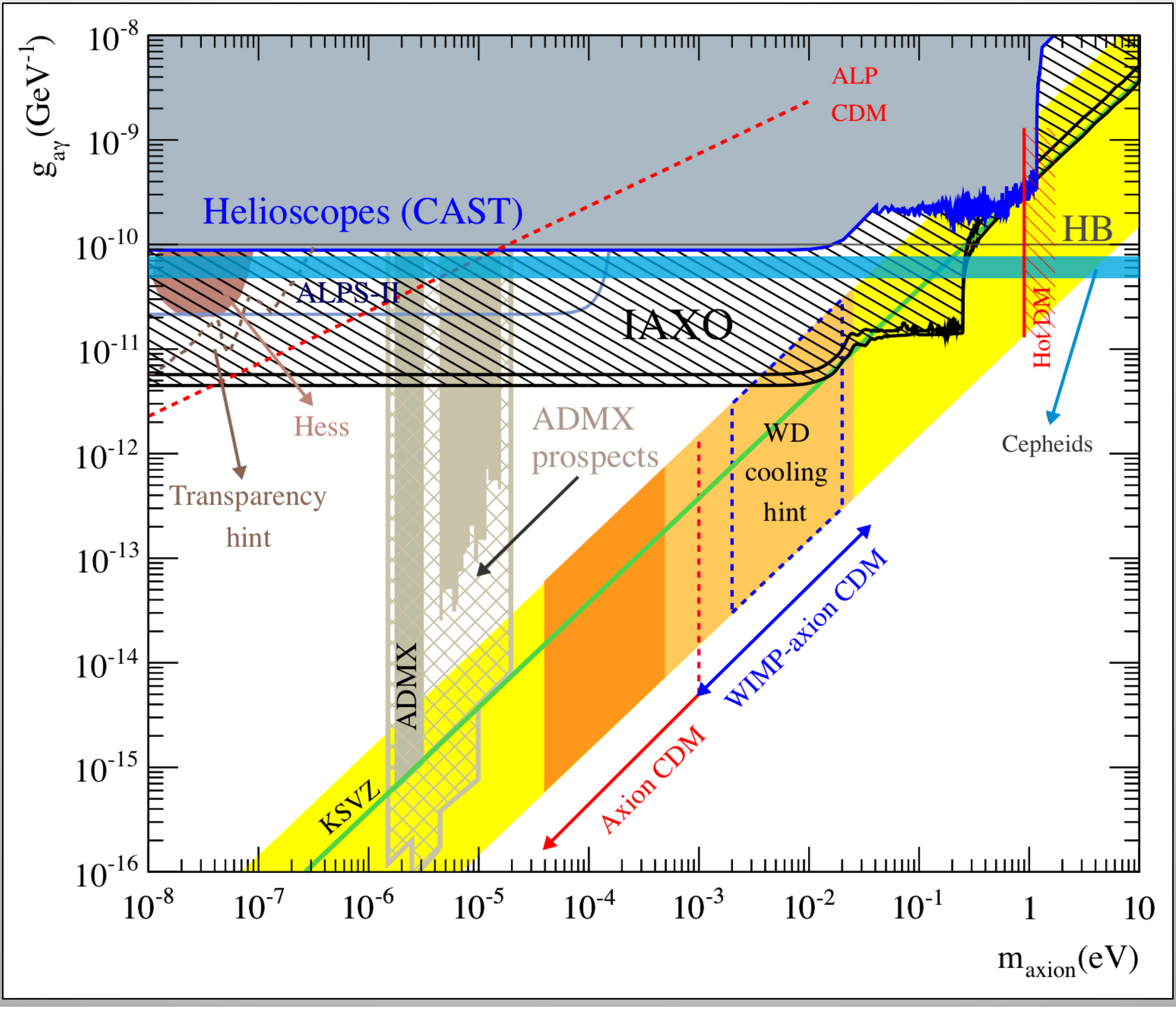
**magnet**
- $B$ = magnetic field
- $L$ = magnet length
- $A$ = cross-sectional area

**exposure**
- $t$ = time

**optics**
- $s$ = spot size
- $\varepsilon_0$ = efficiency

**detectors**
- $b$ = background
- $\varepsilon$ = efficiency

IAXO, relative to CAST:
- $\geq 1050\times$ better (magnet & exposure); $1.4\times$ better (optics); $14\times$ better (detectors)
- $S/N = g_{a\gamma}^4 \geq 20000 \;\rightarrow\; g_{a\gamma} \geq 12\times$ better


$g_{a\gamma}$ (GeV$^{-1}$)
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-15}$
$10^{-16}$
ALP
CDM
Helioscopes (CAST)
HB
ALPS-II
IAXO
Hot DM
Hess
ADMX
prospects
Transparency
hint
WD
cooling
hint
Cepheids
ADMX
WIMP-axion CDM
Axion CDM
KSVZ
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
10
$m_{axion}$ (eV)

# Summary & Conclusions

Axions: solve the Strong-CP problem and are a compelling DM candidate

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Technologies that are under active development (haloscopes):

1. Microwave Cavities:
    - High-Frequency, Large-Volume Tunable Systems with high Q
2. RF Detectors: Quantum Limited (0.25 – 10 GHz): SQUIDs & JPAs
3. Beyond several GHz the standard quantum limit begins to dominate
    - Employ Squeezed States and Eventually Single-Photon-Counters
4. Large Magnets can increase axion conversion signal.

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Stay tuned for additional talks by Jeremy Mardon & Surjeet Rajendran